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Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts

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Abstract

Because of their high energy efficiencies and low emissions, fuel-cell vehicles (FCVs) are undergoing extensive research and development. While hydrogen will likely be the ultimate fuel to power fuel-cell vehicles, because of current infrastructure constraints, hydrogen-carrying fuels are being investigated as transitional fuel-cell fuels. A complete well-to-wheels (WTW) evaluation of fuel-cell vehicle energy and emission effects that examines (1) energy feedstock recovery and transportation; (2) fuel production, transportation, and distribution; and (3) vehicle operation must be conducted to assist decision makers in selecting the fuel-cell fuels that achieve the greatest energy and emission benefits.

A fuel-cycle model developed at Argonne National Laboratory—called the *G*reenhouse gases, *R*egulated *E*missions, and *E*nergy use in *T*ransportation (GREET) model—was used to evaluate well-to-wheels energy and emission impacts of various fuel-cell fuels. The results show that different fuel-cell fuels can have significantly different energy and greenhouse gas emission effects. Therefore, if fuel-cell vehicles are to achieve the envisioned energy and emission reduction benefits, pathways for producing the fuels that power them must be carefully examined.

Keywords: Well-to-wheels analysis; Fuel-cell vehicles; Fuels; Energy use; Greenhouse gas emissions; Hydrogen

1. Introduction

Primarily because of their high efficiencies and zero or near-zero emissions, fuel-cell vehicles (FCVs) are undergoing vigorous research and development (R&D) efforts at major automobile companies worldwide. In fact, some believe that FCVs could revolutionize the automobile industry by replacing internal combustion engine (ICE) technology. Besides investing in FCV R&D efforts, governments and private industries are actively investigating market barriers and vehicle and fuel infrastructure constraints so that introduction of FCVs will be successful when the technology is ready for the mass market.

FCVs based on proton exchange membrane (PEM) technologies require hydrogen (H_2) as the fuel-cell (FC) fuel. Although H_2 is currently produced for fertilizer manufacture, petroleum refining, and other chemical processes, it is not yet produced as a transportation fuel, and the infrastructure for mass production and distribution of H_2 for FCVs is not in place. To overcome the infrastructure barriers, many believe that in the foreseeable future, hydrocarbon fuels may be stored on board FCVs for production of H_2 via fuel processors. Thus, many hydrocarbon fuels, such as methanol (MeOH), gasoline, ethanol (EtOH), and naphtha could serve as fuel-cell fuels.

If H_2 is used to fuel FCVs, they will have zero vehicular emissions. If hydrocarbon fuels are used to power FCVs, they will have near-zero emissions of criteria pollutants and some carbon dioxide (CO_2) emissions. However, even though H_2-powered FCVs offer zero vehicular emissions, production of H_2—especially from natural gas (NG) as it is produced now—can generate a significant amount of emissions and suffer significant energy losses. To provide a complete evaluation of energy and emission impacts of FCVs powered with different fuels, energy use and emissions from wells to pumps (for fuels) and from pumps to wheels (for vehicles) must be taken into account.

In the past several years, some major studies have been conducted to evaluate well-to-wheels (WTW) energy and emission impacts of FCVs powered with different fuels. These studies inevitably differ in their simulations of the production and distribution of fuel-cell fuels and operation of FCVs. The purpose of this paper is to address major

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assumptions regarding fuel production energy efficiencies and FCV fuel economy and provide a WTW analysis of selected vehicle/fuel systems.

2. Approach

2.1. The GREET model

A WTW analysis of a vehicle/fuel system covers all stages of the fuel cycle—from energy feedstock recovery (wells) to energy delivered at vehicle wheels (wheels). A WTW analysis is also called a fuel-cycle analysis in the transportation fuels area and a life-cycle analysis (LCA) for consumer products. Since 1995, with funding from the US Department of Energy (DOE), Argonne National Laboratory has been developing the *G*reenhouse gases, *R*egulated *E*missions, and *E*nergy use in *T*ransportation (GREET) model as an analytical tool for use by researchers and practitioners to estimate WTW energy use and emissions associated with transportation fuels and advanced technology vehicles (ATVs). Argonne released the first version of the GREET model in June 1996 [1]. Since then, Argonne has released a series of GREET versions [2–4]. The GREET model and associated documents are posted at Argonne's GREET website at http://greet.anl.gov.

Argonne has applied the GREET model to analyze WTW energy and emission impacts of various transportation fuels and vehicle technologies [5–8]. Moreover, various 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 own evaluations of vehicle/fuel systems. Methodologies and key assumptions of the GREET model are documented in [2,3,8].

Fig. 1 presents stages and activities covered in GREET WTW simulations of vehicle/fuel systems. A WTW analysis includes the feedstock, fuel, and vehicle operation stages. The feedstock and fuel stages together are called ‘‘well-to-pump’’ (WTP) or ‘‘upstream’’stages, and the vehicle operation stage is called the ‘‘pump-to-wheels’’ (PTW) or ‘‘downstream’’ stage. In GREET, WTW energy and emission results are presented separately for each of the three stages shown in Fig. 1.

2.2. Vehicle propulsion technologies and fuel pathways included in this study

This study focuses on FCV technologies. Because some experts believe that hybrid electric vehicles (HEVs) could be competitive against FCVs in terms of energy and emission reduction benefits, HEVs are included for comparison. The baseline vehicle technology is gasoline vehicles (GVs) equipped with internal combustion engines.

Table 1 lists 18 fuel pathways included in this study. Petroleum-to-gasoline (with 30-ppm sulfur content) is the baseline fuel pathway for GV applications to which other pathways for HEV and FCV applications are compared.

Of the 18 HEV and FCV fuel pathways, 10 are for gaseous or liquid H_2 for FCV applications. Gaseous H_2 (GH_2) needs to be compressed to about 6000 pounds per square inch (psi) in order to store enough energy for a reasonable FCV driving range. Some companies are working on storage cylinders to store H_2 at pressures up to 10,000 psi. FCVs fueled by liquid H_2 (LH_2) can have a longer driving range than those fueled with GH_2. But LH_2 storage requires strict heat insulation for LH_2 tanks and can suffer from the boil-off loss of LH_2. Besides compression and liquid, some other H_2 storage technologies, such as metal hydrides, are currently under R&D. These other storage technologies are not discussed here.

At present, H_2 is primarily produced from NG via steam methane reforming (SMR), a commercially mature technology. While current H_2 production via SMR is in centralized plants, transportation of massive amounts of H_2 from central plants to refueling stations for motor vehicle applications can require a significant capital investment. To avoid the formidable, costly H_2 transportation infrastructure, one option 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 for both GH_2 and LH_2.

A limited amount of H_2 is currently produced from electricity by electrolyzing water. Because the cost of electricity is high in many places, this option may not be economically feasible for many regions. However, electrolyzers

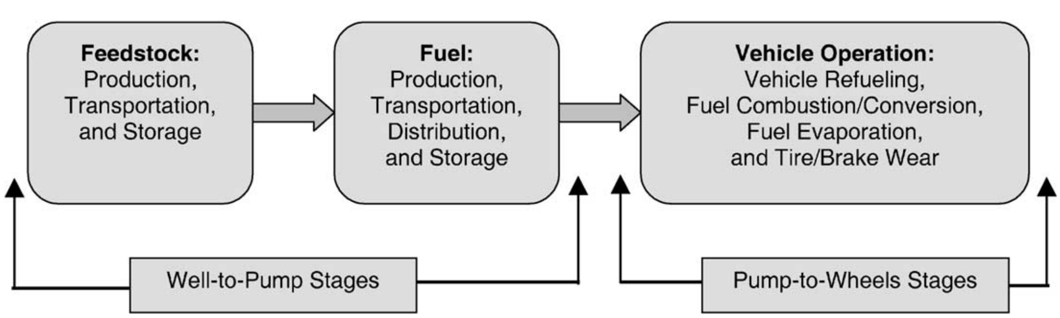

Fig. 1. WTW stages of vehicle/fuel systems covered in the GREET model.

Table 1
Fuel pathways for HEVs and FCVs 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 and gasoline HEVs
Petroleum	LS diesel	LS diesel, with 15-ppm S content, is used to fuel diesel HEVs
NG	CNG	CNG is an HEV fuel
NG	Central gaseous H_2 (GH_2)	GH_2 is produced in central plants, transported to refueling stations via pipelines, and compressed to about 6000 pounds per square inch (psi)
NG	Station GH_2	NG is transported through pipelines to refueling stations, where GH_2 is produced; the GH_2 is compressed to about 6000 psi
NG	Central liquid H_2 (LH_2)	LH_2 is produced in central plants and transported to refueling stations
NG	Station LH_2	NG is transported through pipelines to refueling stations, where LH_2 is produced
US average electricity	GH_2 via electrolysis	GH_2 is produced at refueling stations and compressed to about 6000 psi
US average electricity	LH_2 via electrolysis	LH_2 is produced at refueling stations
Renewable electricity	GH_2 via electrolysis	GH_2 is produced at refueling stations and compressed to about 6000 psi
Renewable electricity	LH_2 via electrolysis	LH_2 is produced at refueling stations
Solar energy	GH_2 via photovoltaic and electrolysis	GH_2 is produced in central locations, transported through pipelines to refueling stations, and compressed to about 6000 psi
Solar energy	LH_2 via photovoltaic and electrolysis	LH_2 is produced in central locations and transported to refueling stations
NG	Methanol	
Petroleum	Gasoline	Gasoline is a fuel-cell fuel with an S content below 10 ppm
Petroleum	Naphtha	Naphtha is a fuel-cell fuel with an S content close to 0 ppm
NG	Naphtha	Naphtha, together with middle distillates, is produced via the Fischer–Tropsch (FT) process and has a 0-ppm S content
Cellulosic biomass	Ethanol	Ethanol is produced from woody and herbaceous biomass

can be small, and electrolysis H_2 production can be carried out at refueling stations to avoid the investment required for H_2 distribution infrastructure. We maintain that electrolysis H_2 could serve remote, less populated areas and provide an intermediate solution until adequate H_2 production and distribution infrastructure is in place. Because the energy 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 US 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).

Various hydrocarbon fuels can be used to produce H_2 onboard FCVs via fuel processors. In our analysis, we include methanol, gasoline, ethanol, and naphtha. 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 onboard fuel processors. Even with this level of sulfur, desulfurization may be needed onboard FCVs before gasoline enters the fuel processor. Ethanol is currently used primarily as a gasoline additive. Although ethanol is now produced primarily from corn, grain-based ethanol production will be limited. DOE has been supporting R&D on ethanol production from cellulosic biomass (i.e. woods and grasses). Because its resource base could support a large quantity of ethanol production, cellulosic ethanol is included in this study.

Naphtha has a low octane number and is not an attractive gasoline blendstock. However, naphtha could be used as a fuel-cell fuel—an application for which octane number does not matter. Currently, naphtha produced from petroleum (crude naphtha) in petroleum refineries is primarily a petrochemical feedstock. With moderate desulfurization, the sulfur content of naphtha can be reduced to near zero. On the other hand, there has been heightened interest in Fischer–Tropsch (FT) diesel production from NG in the past several years. Besides diesel, FT plants produce naphtha. Because NG naphtha can also be used as an FC fuel, we include both crude and NG naphtha in our analysis.

One drawback of a WTW analysis is that it does not address the status of technology development of various vehicle and fuel technologies. Often, researchers include technologies that are at different stages of commercial readiness in their analyses. Because WTW analyses usually do not address the costs and commercial readiness associated with different technologies, they are evaluated together in a way that may give readers the impression that the technologies are at the same level in terms of costs and market readiness. Readers need to be aware that this is usually not the case.

In particular, some of the 18 pathways listed in Table 1 are already in practice in some parts of the world: petroleum to 30-ppm S gasoline, petroleum to 15-ppm S diesel, NG to GH_2 and LH_2 in central plants, electricity to GH_2 and LH_2, NG to methanol, petroleum to naphtha, and NG to CNG. But others are not yet ready for mass production: H_2 production from NG in refueling stations, NG to naphtha via the FT process, and cellulosic biomass to ethanol. Furthermore, some of the pathways will certainly cost more than others. WTW analyses, including this study, usually focus on the energy and emission impacts, not costs, of each pathway. In order to evaluate marketability of fuel pathways, their costs must also be taken into account; however, cost analysis is not the focus of this article.

The analysis in this study is based on applications of HEVs and FCVs in North America. Fuel production pathways and vehicle operation conditions can be different in other parts of the world. Results presented here are applicable to North American applications.

3. Data sources and key assumptions

Key input assumptions regarding both WTP and PTW stages affect WTW energy and emission results. While WTW methodologies are generally similar,[1] studies differ in terms of scope, timeframe, and geographic regions covered. These differences can result in different parametric assumptions regarding energy efficiencies and emissions. This section presents parametric assumptions used in this study.

Although the default version of the GREET model allows users to conduct single point-based simulations (in which a single value is used for an input assumption), the new version of the GREET model—GREET 1.6—is designed to allow users to also conduct stochastic simulations, in which the GREET model can generate energy and emission results with probability distribution functions. In this study, stochastic simulations are conducted. To conduct stochastic simulations with GREET 1.6, users need to have both MS® Excel and Decisioneering's Crystal Ball® software.

3.1. Well-to-pump assumptions

In the past 7 years, Argonne National Laboratory has researched the energy efficiencies and emissions of various transportation fuel production pathways. Argonne has also obtained comments and feedback on fuel production assumptions from some fuel producers. We continue to update and revise key WTP assumptions in the GREET model. The following paragraphs summarize the key assumptions used in this study. Details regarding data sources for these assumptions are presented in [2,3,8].

3.1.1. Petroleum to ICE gasoline, ICE diesel, FC gasoline, and FC naphtha

Beginning in 2004, automakers will be required to meet the US Environmental Protection Agency's (EPAs) Tier 2 vehicle emission standards. Together with vehicle tailpipe standards, EPA requires production of Tier 2 gasoline with an average sulfur content of 30 ppm. We use the 30-ppm S gasoline as the gasoline for baseline GVs. Because sulfur can poison the catalysts used in fuel processors, FCVs may require much lower or even zero sulfur content for gasoline. We assume a sulfur content of less than 10 ppm for FC gasoline. Even with less than 10-ppm S content in gasoline, FCVs may still need some onboard desulfurization measures to remove sulfur from gasoline. Petroleum refineries produce naphtha, which has a low octane number (about 60) and is not an attractive gasoline blendstock. On the other hand, because naphtha contains more hydrogen than some other petroleum hydrocarbons, it could be a good FCV fuel candidate, so we include it in our study. We assume that the sulfur content of naphtha will be reduced to below 10 ppm in petroleum refineries. EPA has established a 15-ppm S diesel fuel requirement. We include this diesel fuel for diesel engine HEVs.

Table 2
Energy efficiencies for petroleum pathway stages

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 with no oxygenate	83.0	84.5	86.0
Petroleum refining to 10-ppm S gasoline with no oxygenate	82.5	84.0	85.5
Petroleum refining to 15-ppm S diesel	85.0	87.0	89.0
Petroleum refining to 10-ppm S naphtha	89.0	91.0	93.0

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

Table 2 presents energy efficiencies for the key stages of the four petroleum-based fuels in our study. The probability-based efficiency assumptions are required for stochastic simulations within GREET. With these probability-based assumptions, we assume the normal distribution curve for the specified parameters except as noted.

Readers may notice that the petroleum refining efficiencies for gasoline and diesel for North American refineries (this study focuses on North American applications) in Table 2 are lower than efficiencies reported elsewhere for European petroleum refineries. One major reason is that while North American refineries are designed for maximum gasoline production, European refineries have a more balanced product slate with relatively high diesel production. North American refineries with maximum gasoline production suffer additional energy efficiency losses.

3.1.2. Natural gas-based fuels

This study includes seven NG-based pathways producing H_2, methanol, naphtha, and CNG (see Table 1). In our past studies, we included both North American (NA) NG and non-North American (NNA) NG to produce these fuels for North American applications. Here, we evaluate NA NG-based pathways. Use of NNA NG for production of transportation fuels for North American applications is subject to additional energy losses during WTP stages.

[1] Some researchers argue that WTW methodologies, as they are used by most researchers now, do not take into account the market effects of introducing a new fuel or vehicle technology [9].

Table 3
Efficiencies of NG-based pathways

Stage	Energy efficiency (%)		
	P20	P50	P80
NG recovery	96.0	97.5	99.0
NG processing	96.0	97.5	99.0
Central GH_2			
GH_2 production[a]	68.0	71.5	75.0
GH_2 compression by NG compressors[b]	82.5	85.0	87.5
GH_2 compression by electric compressors[b]	90.0	92.5	95.0
Central LH_2			
GH_2 production[a]	68.0	71.5	75.0
H_2 liquefaction	65.0	71.0	77.0
Station GH_2			
GH_2 production[a]	62.0	67.0	72.0
GH_2 compression by NG compressors[b]	83.5	86.0	88.5
GH_2 compression by electric compressors[b]	91.5	94.0	96.5
Station LH_2			
GH_2 production[a]	62.0	67.0	72.0
H_2 liquefaction	60.0	66.0	72.0
Methanol production[a]	65.0	67.5	71.0
NG naphtha production[a]	61.0	63.0	65.0
CNG			
NG compression by NG compressors	92.0	93.0	94.0
NG compression by electric compressors[b]	96.0	97.0	98.0

[a] These production plants could be designed with co-production of steam and/or electricity. In this study, we evaluate the plant designs without production of co-products.
[b] A triangle distribution curve is assumed for these stages.

Table 3 presents efficiency assumptions for the seven NG-based pathways. Note that all the NG-based pathways require NG recovery and processing. Plants that produce H_2, methanol, and NG 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 to some extent. In our past studies, we evaluated energy and emission effects of plants with co-produced steam and/or electricity. Here, we evaluate plant designs that do not include steam and/or electricity export.

We evaluate the production of both GH_2 and LH_2 at central plants and at refueling stations. Because refueling stations are small relative to central plants, and because refueling stations may employ partial oxidation technology for H_2 production, the energy efficiency of H_2 production at refueling stations may be lower than that at central plants, which we took into account in our H_2 efficiency assumptions.

The efficiency of GH_2 and NG compression is calculated on the basis of initial pressure, final pressure, and other parameters [8]. Because the initial pressure of H_2 produced at refueling stations could be higher than that of H_2 transported by pipeline from central plants, the compression efficiency of GH_2 produced at refueling stations is higher than that of GH_2 produced at central plants.

Liquid H_2 pathways suffer two major energy losses: GH_2 production and H_2 liquefaction. In addition, LH_2 is subject to boil-off losses. If LH_2 is stored for a long period of time before use, boil-off losses can be significant. Because of these losses, LH_2 pathways generally consume more energy and produce more emissions than GH_2 pathways do.

Table 4
Average electricity generation mix in the united states (from [3])

Coal (%)	Oil (%)	NG (%)	Nuclear (%)	Others[a] (%)
54	1	15	18	12

[a] Including hydropower, geothermal energy, organic wastes, solar energy, and wind power.

3.1.3. Electrolysis hydrogen

H_2 can be produced by electrolysis of water with electricity, and electrolyzers can be designed for H_2 production at refueling stations. Because electricity transmission and distribution infrastructure is already in place throughout most countries, this production option helps avoid long-distance transportation of H_2. However, if H_2 production via electrolysis on a moderate scale is designed for refueling stations, a large amount of electricity could be required. Thus, electricity distribution lines to refueling stations will probably need to be upgraded to allow such H_2 production.

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 analyze two cases of electricity generation: US electricity generation (Table 4) and electricity generation from renewable energy sources (such as hydropower, wind, solar energy, and nuclear power[2]). Besides station H_2 production, we 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 H_2 production from solar energy at refueling stations. We assume that H_2 production from solar energy will be located in regions such as the American Southwest. H_2 produced there, either in gaseous or liquid form, will be transported to refueling stations. The transportation of GH_2 and LH_2 produced from solar energy is similar to the transportation of GH_2 and LH_2 produced from NG in central plants.

Table 5 presents our assumptions regarding electrolysis H_2 production at refueling stations. For electricity delivered to refueling stations, we use an electric transmission and distribution loss of 8%, the US average loss. In our calculations, we use a conversion efficiency of 100% from renewable energy sources to electricity because, for renewable

[2] Technically speaking, nuclear power is not a renewable energy source. However, because a gram of uranium can generate a large amount of electricity, in terms of resource depletion, nuclear power could be treated as a renewable energy source. Mathematically, energy efficiency and GHG emissions are similar among renewable energy sources and nuclear power.

Table 5
Efficiencies of electrolysis hydrogen pathways

Stage	Energy efficiency (%)		
	P20	P50	P80
US average electricity generation			
Oil-fired power plants: steam boilers	32.0	35.0	38.0
NG-fired power plants: steam boilers	32.0	35.0	38.0
NG-fired power plants: combined-cycle turbines[a]	50.0	55.0	60.0
Coal-fired power plants: steam boilers	33.0	35.5	38.0
Coal-fired power plants: advanced technologies	38.0	41.5	45.0
Electricity generation from renewable energy sources[b]	100.0	100.0	100.0
Electrolysis H_2 production at refueling stations			
GH_2 production	67.0	71.5	76.0
H_2 liquefaction (for LH_2)	60.0	66.0	72.0
H_2 compression (for GH_2): electric compressors[a]	91.5	94.0	96.5
Photovoltaic H_2 production in central plants			
GH_2 production[b]	100.0	100.0	100.0
H_2 liquefaction (for LH_2)[b]	100.0	100.0	100.0
GH_2 compression (for GH_2): NG compressors[a]	82.5	85.0	87.5
GH_2 compression (for GH_2): electric compressors[a]	90.0	92.5	95.0

[a] A triangle distribution curve is assumed for these parameters.
[b] An energy efficiency of 100% is used in our calculations because primary energy consumption for electricity generation in these cases is not a concern. In particular, with the conversion of 100%, we account for energy in the electricity generated from these sources, not energy contained in these sources before conversion (e.g. energy in the water behind dams for hydroelectric power plants, energy in uranium for nuclear power plants, solar energy for solar electric power plants, and energy for wind in wind power plants).

sources, resource consumption is not a concern (see footnote b to Table 5).

3.1.4. Cellulosic ethanol

At present, about 1.7 billion gallons of ethanol are used as transportation fuel in the United States. Virtually all of that fuel ethanol is blended with gasoline either in winter to produce oxygenated fuels or in summer to produce reformulated gasoline (RFG) (in Chicago and Milwaukee areas). All of the fuel ethanol is now produced from corn. Because use of methyl tertiary butyl ether (MTBE) will be banned in California and probably nationwide, ethanol could become the dominant oxygenate in RFG in regions besides Chicago and Milwaukee; so the use of fuel ethanol will likely increase significantly in the next few years.

Production of fuel ethanol from grains will be limited because of limited cropland. R&D efforts have been made to develop affordable technologies to produce ethanol from cellulosic biomass. Because cellulosic biomass resources are much greater than grain resources for ethanol production, we include cellulosic ethanol as an FC fuel in this study.

Cellulosic biomass is assumed in this study to be produced at managed farms where trees and grass are grown. The evaluation of cellulosic ethanol here includes: manufacture of fertilizers, cellulosic biomass farming, biomass transportation to ethanol plants, ethanol production, ethanol transportation to refueling stations, and ethanol use in FCVs.

Table 6 lists key WTP assumptions for cellulosic ethanol. For this pathway, we depart from the energy efficiencies we used for other pathways and switch to conversion factors in physical units for all cellulosic ethanol WTP stages because many non-traditional energy items are involved in cellulosic ethanol pathways. Physical units are more transparent than energy efficiencies for cellulosic ethanol.

Use of nitrogen fertilizers contributes to GHG emissions associated with the cellulosic ethanol pathway in two ways. First, fossil fuels are used during fertilizer manufacture and transportation. Second, nitrous oxide (N_2O) emissions from nitrogen fertilizers, through nitrification and denitrification processes on farms, result in GHG emissions. N_2O emissions, which are 310 times as potent as CO_2 emissions in terms of per-unit global warming contribution, are a significant GHG emission source for ethanol pathways. Conversion of land (such as prairie) to tree or grass farms may help increase soil carbon content, which will result in soil

Table 6
Assumptions for cellulosic ethanol pathways

Stage	Parametric assumption		
	P20	P50	P80
Energy use for tree farming: Btu per dry tonne	176,080	234,770	293,460
Energy use for grass farming: Btu per dry tonne	162,920	190,080	271,540
Nitrogen fertilizer use for tree farming: g per dry tonne	532	709	886
Nitrogen fertilizer use for grass farming: g per dry tonne	7,980	10,63	13,290
N_2O emissions in biomass farms: N in N_2O as % of N in N fertilizers	0.8	1.15	1.5
Soil CO_2 sequestration in tree farms: g per dry tonne[a]	−225,000	−112,500	0
Soil CO_2 sequestration in grass farms: g per dry tonne[a]	−97,000	−48,500	0
Ethanol yield: gal per dry tonne of trees	76	87	98
Ethanol yield: gal per dry tonne of grass	80	92	103
Electricity credit of tree-based ethanol plants: kWh/gal[a]	−1.73	−1.15	−0.56
Electricity credit of grass-based ethanol plants: kWh/gal[a]	−0.87	−0.57	−0.28

[a] A triangle distribution curve is assumed for these parameters.

CO_2 sequestration, which we consider in this analysis. Soil carbon sequestration is an important factor in determining cellulosic ethanol's GHG benefits. However, data on soil carbon sequestration are very scarce.

In cellulosic ethanol plants, the cellulosic and semi-cellulosic portions of biomass are converted into ethanol. The lignin portion of biomass can be burned to provide needed steam in the plants. Although burning of lignin produces CO_2 emissions, they are initially taken from the atmosphere by trees or grasses. Cellulosic plants could be designed with co-generation systems to produce both steam and electricity. Besides use inside of ethanol plants, some extra electricity can be exported outside of the plants. We consider potential electricity export from ethanol plants. The exported electricity can displace electricity generation in conventional electric power plants. We calculate energy and emissions credits by considering the displacement of conventional electricity generation.

3.2. Pump-to-wheels assumptions

The key PTW parameter determining WTW energy use and GHG emissions associated with vehicle/fuel systems is the fuel economy of advanced vehicles. Models for predicting the fuel economy of ICE vehicle technologies have been developed and calibrated with measured fuel economy data. Prediction of ICE fuel economy is generally reliable. Recently, efforts have been made to develop modeling capabilities to predict the fuel economy of advanced vehicle technologies such as HEVs and FCVs. Progress has been made—especially in the last few years—in developing modeling capabilities for HEV fuel economy. However, development of FCV fuel economy modeling capabilities is still in its infancy. This section summarizes several studies that were recently completed to predict the fuel economy of HEVs and FCVs (see Appendix A). On the basis of these completed studies, we develop fuel economy assumptions for this study.

Weiss et al. [10] of the Massachusetts Institute of Technology (MIT) completed a study to evaluate life-cycle energy and emission impacts of AVTs. The MIT study uses a vehicle simulation model to predict fuel economy in 2020 for gasoline ICE vehicles; diesel ICE vehicles; HEVs fueled with either gasoline or diesel; battery-powered electric vehicles (EVs); and FCVs fueled with gasoline, methanol, and H_2. Fuel economy simulations were conducted for an average-size passenger car, such as the Toyota Camry, and with the US federal test procedure (FTP) urban and highway cycles. All vehicle technologies were assumed to provide a constant peak power-to-mass ratio of 75 W/kg, have a 600 km driving range (except for EVs), and have the same vehicle size. The FCV type simulated was hybrid FCVs. That is, batteries, together with fuel-cell stacks, were included to power vehicles.

General Motors Corporation [7] conducted vehicle simulations for a WTW analysis. The simulations included conventional vehicles fueled with gasoline, diesel, E85 (85% ethanol and 15% gasoline by volume), and CNG; parallel-configured, charge-sustaining HEVs fueled with gasoline, diesel, and E85; and stand-alone and hybrid FCVs fueled with gasoline, methanol, ethanol, and H_2. Each vehicle type was assumed to meet specified performance requirements such as acceleration ability and gradeability for pre-determined peak acceleration and top speed. A General Motors proprietary model was used to simulate a full-size pickup truck (Chevrolet Silverado) with different propulsion system/fuel combinations. Vehicle technologies were assumed to be in place in around 2010.

Thomas et al. [11] of Directed Technologies, Inc. (DTI) conducted simulations of FCVs and HEVs for the Ford Motor Company and DOE. The researchers simulated a passenger car similar to the Mercury Sable with aluminum-intensive vehicle (AIV) material composition; this vehicle has 270 kg less vehicle mass than a conventional Sable. They included H_2-fueled FCVs with and without recovering regenerative energy; FCVs fueled with gasoline and methanol for a probable and a best case; and parallel and series design ICE HEVs fueled with diesel fuel, CNG, and H_2. Besides the US FTP urban and highway cycles, they simulated each vehicle at 1.25 times the speed of the urban and highway cycles in order to realistically address real-world power demand. We summarize their simulated results under the FTP cycles here.

In 1999, Thomas updated DTI's earlier vehicle simulation results for DOE [12]. Relative to his 1998 estimates, Thomas' 1999 estimates showed lower fuel economy, especially for methanol- and gasoline-powered FCVs and gasoline- and diesel-fueled HEVs.

Ogden et al. [13] of Princeton University analyzed FCVs fueled with H_2, methanol, and gasoline. Ogden et al. used a vehicle simulation model developed at Princeton University and selected the Partnership for a New Generation of Vehicles (PNGV)-specified car size to simulate FCV fuel economy. They assumed hybrid designs for FCVs. Compared with other studies, Ogden et al. showed that gasoline-powered FCVs equipped with partial oxidation fuel processors achieved higher fuel economy than methanol-powered FCVs equipped with steam reforming fuel processors. They maintained that partial oxidation fuel processors had higher overall energy efficiency than steam reforming fuel processors.

Santini et al. of Argonne National Laboratory [14] reviewed the fuel economy of HEVs and baseline GVs under different driving cycles and for different HEV designs. The Argonne researchers showed that, depending on vehicle designs and performance requirements, HEVs could have very different relative fuel economies compared with GVs. One set of HEV fuel economy results presented in their paper is from Argonne's analysis of the total energy-cycle energy and emission impacts of HEVs. That set of the results is cited in this paper. The Argonne simulations were conducted by using the ADVISOR vehicle simulation model developed at the National Renewable Energy Laboratory (NREL). In conducting HEV simulations, Argonne separated HEVs into two general groups: mild and full HEVs.

For a mild HEV, a lower portion of the power demand is met by the electric power system (electric motors and batteries) than for a full HEV. Their results show that fuller hybridization and increased power demand for HEVs result in higher fuel economy gains by HEVs.

Kumar et al. [15] of Argonne National Laboratory simulated the fuel economy of gasoline FCVs with an FCV simulation model (GC tool) developed at Argonne. The GC tool model includes detailed simulations of onboard fuel processors and fuel-cell stacks. Kumar et al. did not simulate baseline GV fuel economy, but their FCV simulations were based on a PNGV type of passenger car (i.e. a mid-size sedan with lightweight materials and improved aerodynamics). They specified that FCVs would meet the acceleration goal of 12 s for 0–60 mph and simulated both stand-alone and hybrid FCV designs. Their hybrid FCV design was shown to have lower fuel economy than the stand-alone FCV design, although the difference was small.

Appendix A presents estimated fuel economy and fuel economy ratios from the reviewed studies. Table 7 summarizes fuel economy ratios by vehicle type. For a given vehicle type, the ratio could be different among the studies reviewed or within a given study. The differences reflect future technology uncertainties, different vehicle design options, and differences in vehicle performance attributes. Fig. 2 graphically shows the ratios of each vehicle technology included in Table 7. Because of limited results, standalone and hybrid FCV designs are combined together in Fig. 2. The number next to each vehicle type title in the chart represents the number of studies that simulated the given type. Although the range of fuel economy ratios for a given vehicle type reflects technology uncertainties, vehicle design options, and performance attributes, it is also significantly influenced by the number of studies. The more studies, the wider the range. Thus, the results in the figure cannot be used solely to establish fuel economy distribution functions for the vehicle types.

Table 8 presents fuel economy distribution assumptions established during this study for HEVs and FCVs. The distribution assumptions listed in Table 8 are based primarily on the results in Appendix A, Table 7, and Fig. 2. A sample of vehicle fuel economy distribution functions incorporated in the GREET model is presented in Fig. 3. With these distribution functions and the WTP distribution functions presented in the previous section, the GREET model was run to generate energy use and emission results with probability distributions.

Table 7
Summary of fuel economy ratios of HEVs and FCVs to baseline gasoline vehicles

Vehicle type Data Source	Fuel economy ratio under driving cycle		
	Urban	Highway	Combined
H_2 FCV: standalone	2.39	1.82	2.14–2.68
General Motors [7]	2.39	1.82	2.14
DTI [12]	N/A[a]	N/A	2.53–2.68
H_2 FCV: hybrid	2.21–2.96	1.78–2.22	2.18–2.73
MIT [10]	2.21	2.13	2.18
General Motors [7]	2.96	1.78	2.38
DTI [11]	2.81–3.13	2.16–2.22	2.54–2.73
DTI [12]	N/A	N/A	2.56–2.70
Princeton [13]	2.81	2.14	2.52
MeOH FCV: standalone	1.66	1.30	1.50
General Motors [7]	1.66	1.30	1.50
MeOH FCV: hybrid	1.32–2.06	1.31–1.67	1.32–2.04
MIT [10]	1.32	1.31	1.32
General Motors [7]	2.06	1.32	1.71
DTI [11]	2.05–2.31	1.50–1.67	1.81–2.04
DTI [12]	N/A	N/A	1.66–2.00
Princeton [13]	1.74	1.47	1.64
Gasoline FCV: standalone	1.51–2.08	1.14–2.09	1.35–2.08
General Motors [7]	1.51	1.14	1.35
Argonne [15]	1.69–2.08	1.73–2.09	1.76–2.08
Gasoline FCV: hybrid	0.98–1.83	0.98–1.49	0.98–1.77
MIT [10]	0.98	0.98	0.98
General Motors [7]	1.83	1.14	1.50
DTI [11]	1.44–2.01	1.05–1.46	1.28–1.77
DTI [12]	N/A	N/A	1.19–1.59
Princeton [13]	1.83	1.49	1.69
EtOH FCV: standalone	1.58	1.20	1.42
General Motors [7]	1.58	1.20	1.42
EtOH FCV: hybrid	1.93	1.20	1.57
General Motors [7]	1.93	1.20	1.57
Gasoline HEV	1.33–1.88	1.00–1.62	1.21–1.73
MIT [10]	1.65	1.62	1.64
General Motors [7]	1.37	1.00	1.21
Argonne [14]	1.33–1.88	1.11–1.51	1.24–1.73
Diesel HEV	1.67–2.69	1.19–1.84	1.46–2.29
MIT [10]	1.94	1.84	1.91
General Motors [7]	1.67	1.19	1.46
DTI [11]	1.81–2.69	1.39–1.80	1.64–2.29
DTI [12]	N/A	N/A	1.41–2.25
CNG HEV	1.64–2.45	1.26–1.66	1.34–2.08
MIT [10]	1.72	1.66	1.70
DTI [11]	1.64–2.45	1.26–1.63	1.48–2.08
DTI [12]	N/A	N/A	1.34–2.03

[a] N/A = not available.

4. Results

On the basis of the WTP and PTW distribution assumptions presented in Section 3, we use the GREET model to conduct stochastic simulations of WTW energy use and GHG emissions for vehicle/fuel systems included in this study. GREET generates results for a given output item with a probability distribution. Fig. 4 shows a sample output profile from Crystal Ball stochastic simulations.

4.1. Well-to-pump energy efficiencies

Fig. 5 presents WTP energy efficiencies for 17 fuel pathways. These efficiencies are affected by the energy losses from primary energy feedstocks to fuels available

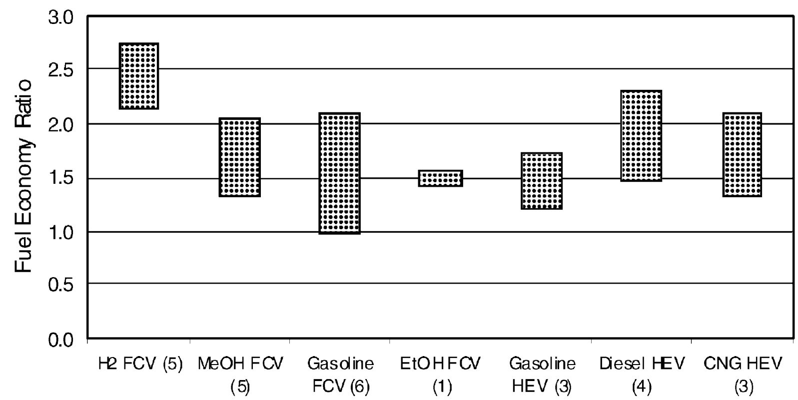

Fig. 2. Fuel economy ratios of FCVs and HEVs to baseline GVs (the number next to each vehicle type represents the number of studies for the type).

Table 8
Distribution functions for vehicle fuel economy ratios (relative to gasoline vehicle fuel economy, the weibull distribution curve is assumed)[a]

Vehicle type	Low-bound value	P50 value	P95 value
Baseline GV fuel economy	22.0	27.0	33.0
Gasoline and CNG HEV	1.20	1.40	1.70
Diesel HEV	1.40	1.60	1.95
H_2 FCV	2.10	2.35	2.60
MeOH FCV	1.30	1.60	1.80
Gasoline and naphtha FCV	1.00	1.50	1.70
EtOH FCV	1.10	1.55	1.80

[a] The fuel economy of baseline GVs and the fuel economy ratios of HEVs and FCVs are for a mid-size car to be produced in 2010. 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.

at fuel pumps in refueling stations. In this chart and the charts in Figs. 6–9, the bars represent average values, and the lines on the bars represent ranges from a probability of 10% to a probability of 90%.

The crude-to-RFG pathway has an efficiency of about 80%. Three fuels—CNG, LS diesel, and crude naphtha—have WTP efficiencies higher than the gasoline efficiency. This means that even if vehicles using these three fuels achieve the same miles per gallon (mpg) as baseline GVs, these vehicles will have better WTW energy efficiencies than do GVs. On the other hand, the remaining 13 fuel pathways have lower WTP efficiencies than GVs. Vehicles using these fuels must have higher mpg to achieve overall WTW energy efficiency gains over baseline GVs. The worst two pathways are GH_2 and LH_2 produced via electrolysis with average US electricity generation. The LH_2 WTP efficiency is about 20%—one-fourth of the efficiency of RFG. This result suggests that FCVs fueled with LH_2 made via this pathway need to have a 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 GH_2 need to achieve a fuel economy level at least 2.7 times that of GVs. In general, production of H_2 is subject to significant energy losses. The cellulosic ethanol pathway is subject to significant energy losses as

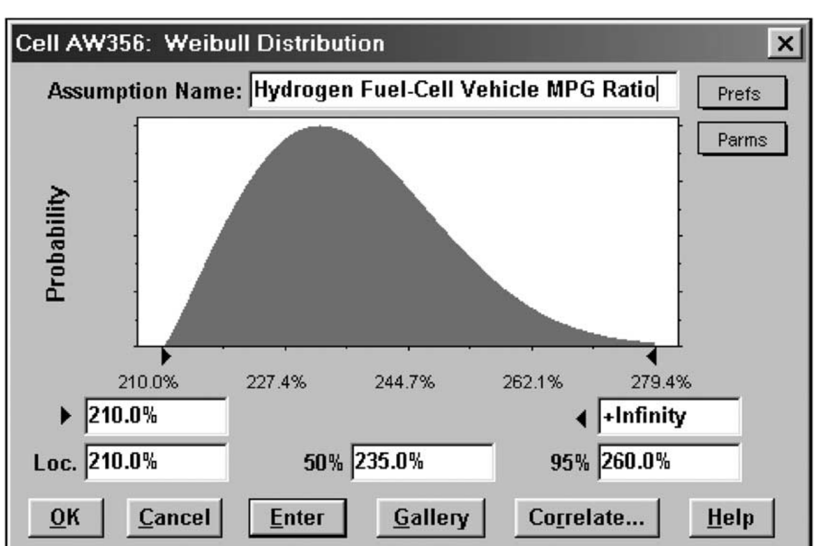

Fig. 3. A sample distribution function for stochastic simulations: H_2 FCV fuel economy ratio.

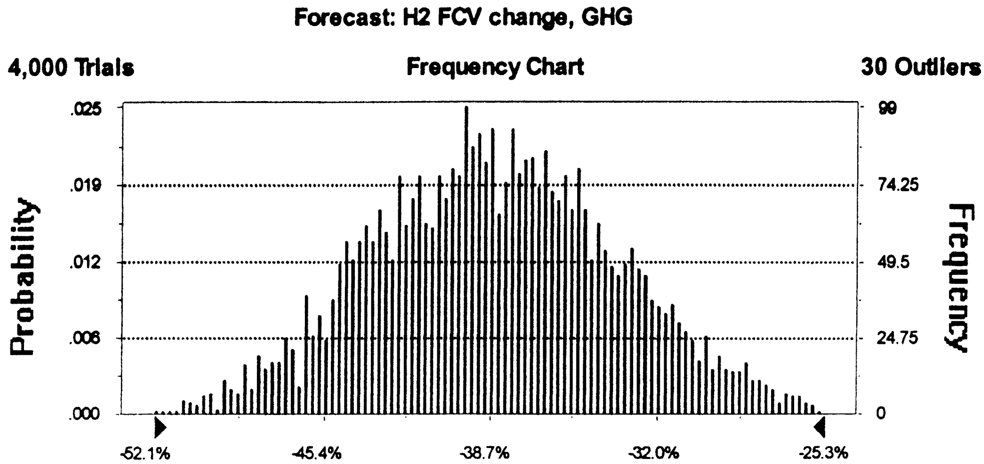

Fig. 4. Sample outputs of crystal ball stochastic simulations: GHG emission change by FCVs fueled with LH_2 produced in central plants from NG (relative to emissions of baseline GVs).

well. However, most of the energy consumed during the cellulosic pathway is renewable energy (as discussed below). This chart clearly shows that different fuel pathways are subject to different WTP energy losses. Thus, WTW analysis must be conducted to adequately evaluate vehicle propulsion systems that employ different fuels.

4.2. Well-to-wheels total energy use changes

Fig. 6 presents WTW total energy use changes by HEVs and FCVs relative to baseline GVs fueled with RFG. These energy uses result from WTP efficiencies (Fig. 5) and relative fuel economy (Table 8). On a WTW basis, FCVs fueled with station LH_2 made from NG, GH_2, and LH_2 based on US average electricity generation, LH_2 from renewable electricity (such as hydropower, wind, etc.), and cellulosic ethanol increase per-mile total energy use. The increases are caused by significant energy losses during the WTP stages for these fuels. The WTP energy losses are so large that even the improved mpg of FCVs is not enough to offset the losses for these options. On the other hand, the three HEV options (fueled with RFG, CNG, and LS diesel) achieve 30–40% reductions in total energy use. Among the other H_2 FCV options, total energy use is reduced by 20–50%. FCVs fueled with methanol, gasoline, and crude naphtha achieve 20–50% reductions. NG naphtha-based FCVs achieve small reductions, because production of naphtha from NG is subject to significant energy losses. This chart shows that even efficient FCVs may not achieve energy benefits if inefficient fuel pathways are used to provide fuels for them.

4.3. Well-to-wheels fossil energy use changes

Fig. 7 shows the changes in WTW fossil energy use (petroleum, NG, and coal) for HEVs and FCVs. Fossil energy use changes differ significantly from total energy use changes for the fuels based on renewable sources, which include GH_2 and LH_2 from solar photovoltaic panels, GH_2

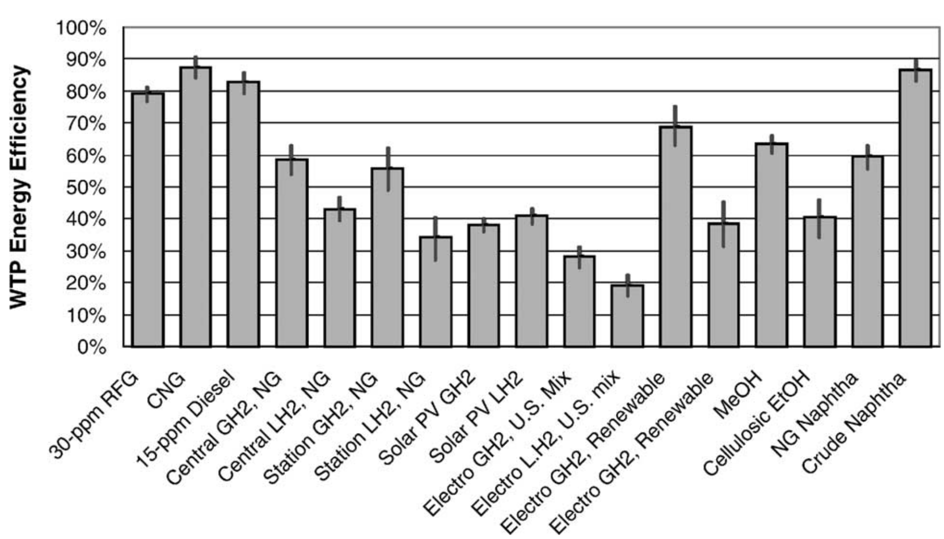

Fig. 5. Well-to-pump energy efficiencies.

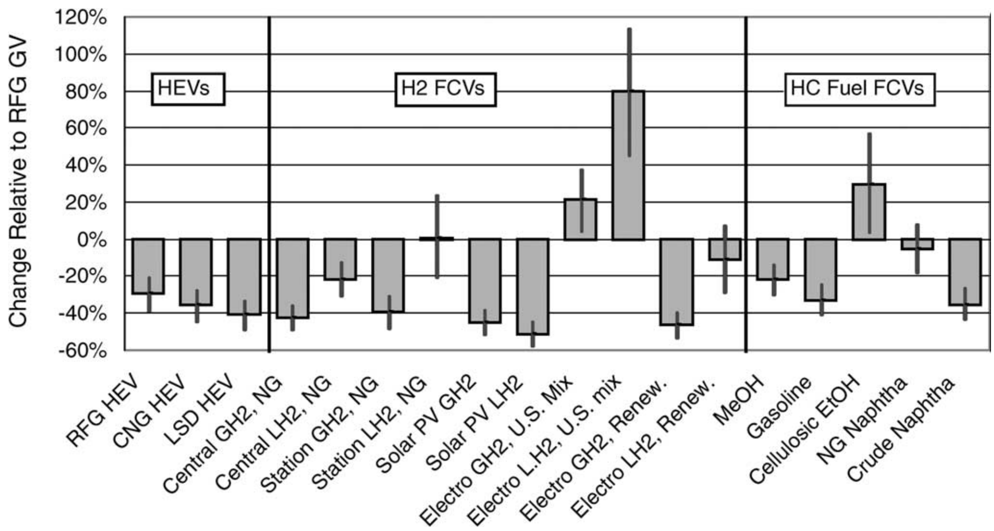

Fig. 6. Changes in well-to-wheels total energy use (relative to baseline GVs).

and LH_2 from renewable electricity via electrolysis, and cellulosic ethanol. 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 researcher to take into account the type, as well as the number, of energy sources used in producing transportation fuels.

4.4. Well-to-wheels petroleum use changes

Fig. 8 presents the changes in WTW petroleum use by HEVs and FCVs. Except for four systems using petroleum-based fuels (RFG HEVs, LS diesel HEVs, gasoline FCVs, and crude naphtha FCVs), all other vehicle/fuel systems almost eliminate petroleum use. The reductions by the four petroleum-based systems are primarily from vehicle fuel economy improvements.

4.5. Well-to-wheels greenhouse gas emissions changes

Fig. 9 shows the changes in WTW GHG emissions for HEVs and FCVs. GHG emissions here include CO_2, methane (CH_4), and 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 GH_2 and LH_2 produced with average US electricity and station LH_2 from NG, all other vehicle/fuel systems reduce GHG emissions. The five renewable fuel options (GH_2 and LH_2 from solar photovoltaic, GH_2 and LH_2 from renewable electricity, and cellulosic ethanol) reduce GHG emissions by more than 90%. Other vehicle/fuel options reduce GHG emissions by 30–60%. The three HEV options reduce GHG emissions to levels comparable to those achieved by FCVs fueled with non-renewable fuels.

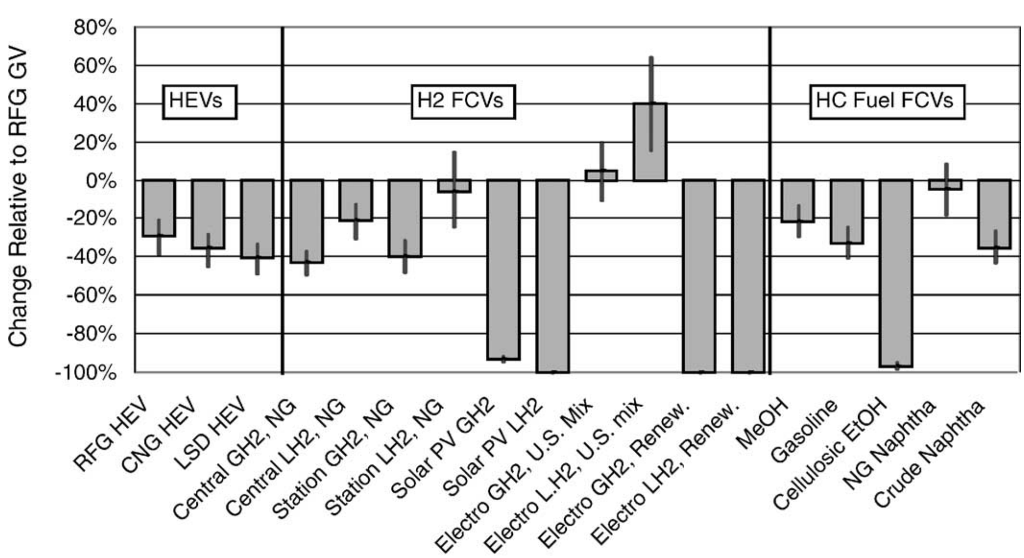

Fig. 7. Changes in well-to-wheels fossil energy use (relative to baseline GVs).

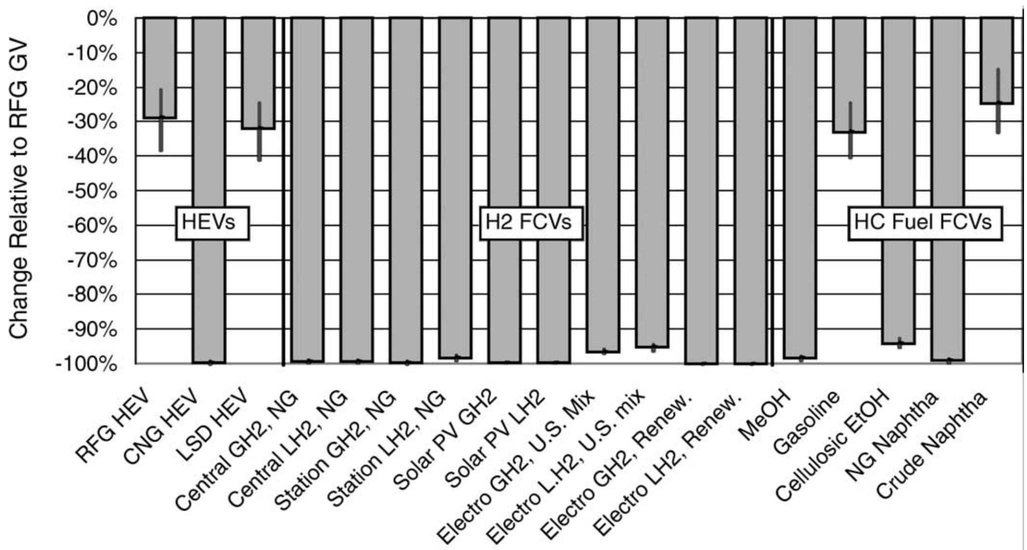

Fig. 8. Changes in well-to-wheels petroleum use (relative to baseline GVs).

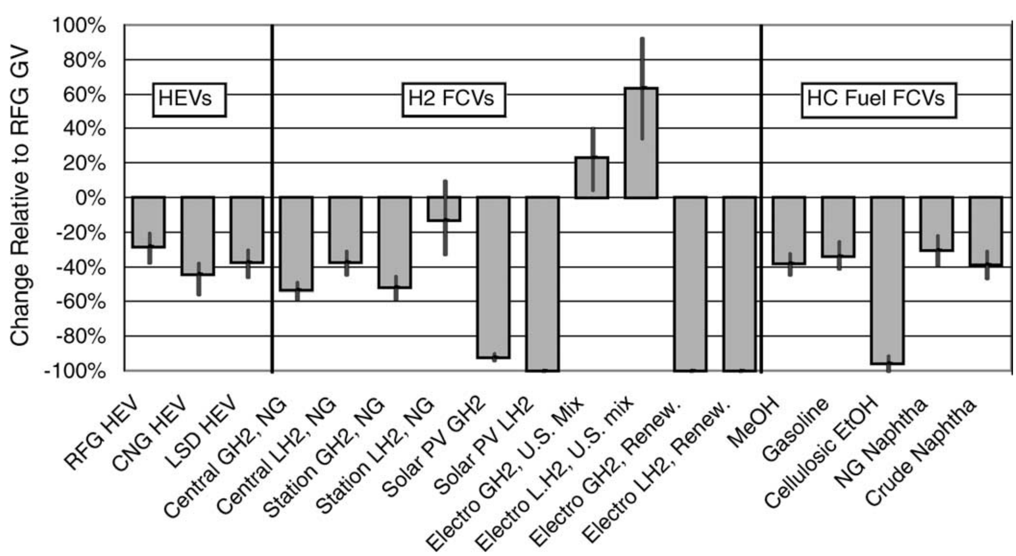

Fig. 9. Changes in well-to-wheels greenhouse gas emissions (relative to baseline GVs).

5. Conclusions

This study demonstrates that different fuel options for FCVs can have very different energy and GHG emission effects. WTW analyses are necessary for adequately evaluating fuel/vehicle systems. Among the vehicle/fuel systems evaluated in this study, FCVs fueled by H_2 produced via electrolysis consume more energy than do baseline GVs. FCVs fueled with cellulosic ethanol consume more total energy, but much less fossil energy than do GVs. HEVs and other FCV options achieve significant energy reduction benefits. All HEV and FCV options, except FCVs fueled by H_2 produced from average US electricity and station LH_2 from NG, help reduce GHG emissions significantly. If the goal of introducing FCVs is to achieve significant energy and GHG emission reduction benefits, the pathways used to produce fuels for FCVs must be carefully examined.

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Appendix A. Summary of fuel economy of baseline gasoline vehicles and advanced vehicle technologies from completed studies

Vehicle type	Vehicle mass (kg)	Gasoline-equivalent MPG			MPG ratio to baseline GV		
		Urban	Highway	Combined	Urban	Highway	Combined
Weiss et al.: a Toyota Camry-like car, fuel economy ratios here are based on year 2020 GV fuel economy [10]							
1996 GV	1322	23.7	35.2	27.8	NA[a]	NA	NA
2020 baseline GV	1108	37.9	52.1	43.2	NA	NA	NA
2020 advanced GV	1007	42.4	60.8	49.1	1.12	1.17	1.14
2020 advanced DV	1062	47.9	70.8	56.0	1.26	1.36	1.30
2020 gasoline HEV	1023	62.7	84.2	70.8	1.65	1.62	1.64
2020 diesel HEV	1060	73.6	96.1	82.3	1.94	1.84	1.91
2020 CNG HEV	1039	65.3	86.5	73.4	1.72	1.66	1.70
2020 gasoline hybrid FCV	1330	37.2	50.9	42.3	0.98	0.98	0.98
2020 MeOH hybrid FCV	1253	49.9	68.4	56.9	1.32	1.31	1.32
2020 H_2 hybrid FCV	1179	83.7	110.8	94.1	2.21	2.13	2.18
2020 EV	1176	130.8	179.5	149.0	3.45	3.45	3.45
General motors et al.: Silverado pickup truck, 2010 technologies [7]							
Baseline SI vehicle	2200[b]	17.4	25.0	20.2	NA	NA	NA
Diesel CIDI vehicle	NP[c]	20.2	30.4	23.8	1.16	1.22	1.18
E85 SI vehicle	NP	17.4	25.0	20.2	1.00	1.00	1.00
CNG SI vehicle	NP	17.0	24.7	19.8	0.98	0.99	0.98
Gasoline SI HEV	NP	23.8	25.1	24.4	1.37	1.00	1.21
Diesel CIDI HEV	NP	29.1	29.8	29.4	1.67	1.19	1.46
E85 SI HEV	NP	23.8	25.1	24.4	1.37	1.00	1.21
Gasoline standalone FCV	NP	26.2	28.6	27.2	1.51	1.14	1.35
Gasoline hybrid FCV	NP	31.9	28.5	30.2	1.83	1.14	1.50
MeOH standalone FCV	NP	28.8	32.4	30.3	1.66	1.30	1.50
MeOH hybrid FCV	NP	35.8	33.0	34.5	2.06	1.32	1.71
EtOH standalone FCV	NP	27.5	30.0	28.6	1.58	1.20	1.42
EtOH hybrid FCV	NP	33.5	29.9	31.8	1.93	1.20	1.57
H_2 standalone FCV	NP	41.6	45.4	43.2	2.39	1.82	2.14
H_2 hybrid FCV	NP	51.5	44.5	48.1	2.96	1.78	2.38
Thomas et al.: a Mercury Sable-like car, MPG ranges reflect a probable and a best case [11]							
GV	1304	25.5	38.5	30.1	NA	NA	NA
H_2 hybrid FCV	1291	71.6–79.7	83.2–85.4	76.4–82.2	2.81–3.13	2.16–2.22	2.54–2.73
MeOH hybrid FCV	1390–1413	52.4–58.9	57.6–64.4	54.6–61.3	2.05–2.31	1.50–1.67	1.81–2.04
Gasoline hybrid FCV	1387–1475	36.8–51.2	40.6–56.1	38.4–53.3	1.44–2.01	1.05–1.46	1.28–1.77
Diesel HEV	1245	46.2–68.5	53.7–69.4	49.3–68.9	1.81–2.69	1.39–1.80	1.64–2.29
CNG HEV	1219	41.9–62.4	48.4–62.9	44.6–62.6	1.64–2.45	1.26–1.63	1.48–2.08
H_2 ICE HEV	1247	42.9–64.7	50.0–65.1	45.8–64.9	1.68–2.54	1.30–1.69	1.52–216
Thomas et al.: results are for PNGV/AIV-Sable vehicles, respectively, mass is for test weight [12]							
GV	1042/1304	NP	NP	40/32	NA	NA	NA
CIDI parallel HEV	990/1245	NP	NP	90/64	NA	NA	2.25/2.00
CIDI load following HEV	1082/1361	NP	NP	66/55	NA	NA	1.65/1.72
CIDI series HEV—AIV	1185/1472	NP	NP	63/45	NA	NA	1.58/1.41
CNG parallel HEV	969/1200	NP	NP	81/62	NA	NA	2.03/1.94

Appendix A. (*Continued*)

Vehicle type	Vehicle mass (kg)	Gasoline-equivalent MPG			MPG ratio to baseline GV		
		Urban	Highway	Combined	Urban	Highway	Combined
CNG load following HEV	1057/1308	NP	NP	62/46	NA	NA	1.55/1.44
CNG series HEV	1158/1435	NP	NP	59/43	NA	NA	1.48/1.34
H_2 load following HEV	1117/1366	NP	NP	63/52	NA	NA	1.58/1.63
H_2 series HEV	1229/1366	NP	NP	60/44	NA	NA	1.50/1.38
Gasoline FCV—best	1099/1387	NP	NP	63/51	NA	NA	1.58/1.59
Gasoline FCV—probable	1172/1475	NP	NP	52/38	NA	NA	1.30/1.19
MeOH FCV—best	1110/1390	NP	NP	80/61	NA	NA	2.00/1.91
MeOH FCV—probable	1119/1414	NP	NP	72/53	NA	NA	1.80/1.66
H_2 standalone FCV	1023/1283	NP	NP	107/81	NA	NA	2.68/2.53
H_2 hybrid FCV	1042/1291	NP	NP	108/82	NA	NA	2.70/2.56
Ogden et al. [13]							
GV	1182[d]	35.6[d]	53.7[d]	42[d]	NA	NA	NA
H_2 hybrid FCV	1170	100	115	106	2.81	2.14	2.52
MeOH hybrid FCV	1287	62	79	69	1.74	1.47	1.64
Gasoline hybrid FCV	1395	65	80	71	1.83	1.49	1.69
Santini et al.: the set from Argonne's own HEV simulations in that paper is selected here [14]							
12-second acceleration for 0–60 mph							
GV	1175	32.2	47.1	37.5	NA	NA	NA
Mild parallel HEV	1246	42.7	52.4	46.6	1.33	1.11	1.24
Full parallel HEV	1247	46.7	57.0	50.9	1.45	1.21	1.36
10-second acceleration for 0–60 mph							
GV	1248	27.7	41.6	32.6	NA	NA	NA
Mild parallel HEV	1321	41.3	50.4	45.0	1.49	1.21	1.38
Full parallel HEV	1328	45.2	55.7	49.4	1.63	1.34	1.52
8-second acceleration for 0–60 mph							
GV	1366	22.6	35.0	26.9	NA	NA	NA
Mild parallel HEV	1453	37.9	47.2	41.6	1.68	1.35	1.55
Full parallel HEV	1466	42.5	52.8	46.6	1.88	1.51	1.73
Kumar et al.: a PNGV type of cars, results are for stand-alone FCV designs [15]							
Gasoline FCV: light weight	1043	76	90	82	2.01[e]	1.73[e]	1.90[e]
Gasoline FCV: aerodynamic	1379	64	97	76	1.69[e]	1.86[e]	1.76[e]
Gasoline FCV: LW + aero	1043	79	109	90	2.08[e]	2.09[e]	2.08[e]

[a] Not applicable.
[b] This is the curb weight for 2002 MY Silverado.
[c] Not presented in the study.
[d] Ogden et al. did not present fuel economy of a baseline GV. According to Ogden, their baseline GV was a lightweight vehicle similar to DTIs baseline vehicle. The weight of Princeton's baseline is estimated here with DTI baseline vehicle weight and the difference in H_2 FCV weight between Princeton and DTI. Ogden stated that their baseline GV achieved 42 MPG of fuel economy under the 55/45 combined cycle. Using the difference in combined-cycle fuel economy between Princeton and DTI, we derived urban and highway fuel economy of Princeton's baseline vehicle.
[e] Kumar et al. did not estimate fuel economy of a baseline GV. The fuel economy values of the 2020 baseline GV from the MIT study are used here to calculate fuel economy ratios.

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