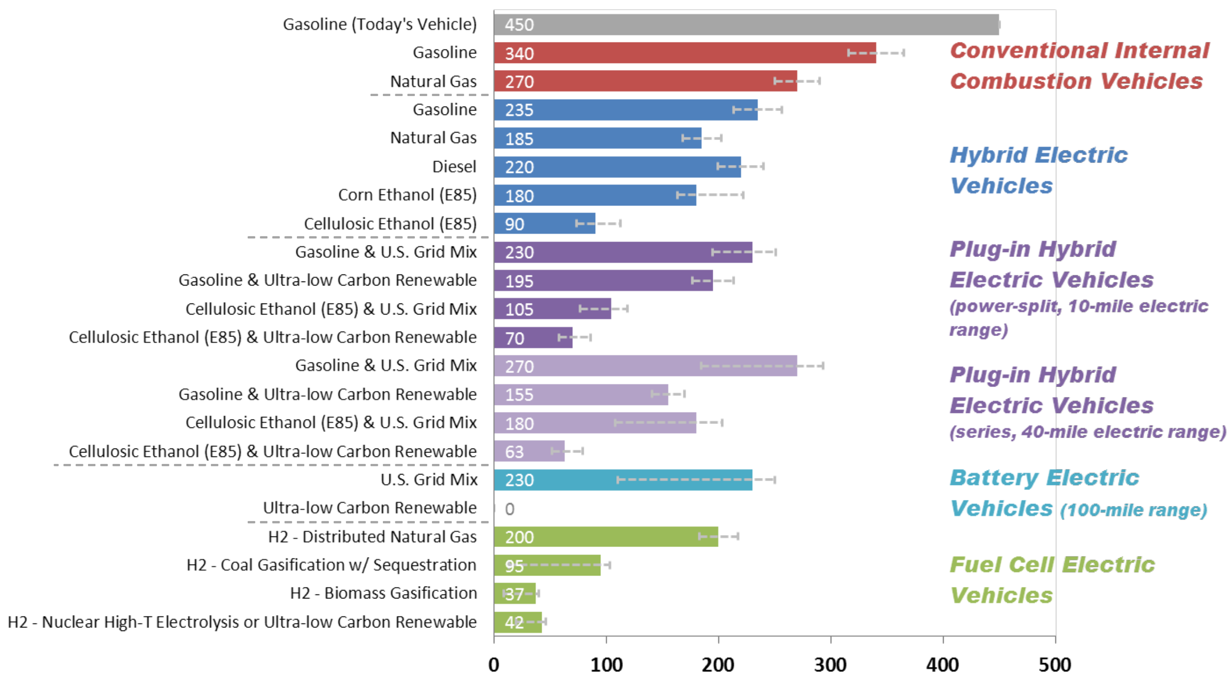
Program Record (Offices of Vehicle Technologies & Fuel Cell Technologies)	
Record #: 10001	**Date:** October 5, 2010
Title: Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles	
Originator: Tien Nguyen & Jake Ward	
Approved by: Sunita Satyapal Pat Davis	**Date:** October 25, 2010

<u>Items:</u>

DOE is pursuing a portfolio of technologies with the potential to significantly reduce greenhouse gases (GHG) emissions and petroleum consumption. This record documents the assumptions and results of analyses conducted to estimate the GHG emissions and petroleum energy use resulting from several fuel/vehicle pathways, for a future mid-size car and a mid-size sport utility vehicle (SUV). The results are summarized graphically in the following figures.

Well-to-Wheels Greenhouse Gases Emissions for Future Mid-Size Car

(Grams of CO_2-equivalent per mile)



Low/high band: sensitivity to uncertainties associated with projected fuel economy of vehicles and attributes of fuels pathways, e.g., electricity credit for ethanol or hydrogen, electric generation mix, fraction of biomass-to-hydrogen plants with carbon sequestration, etc.

<u>Notes:</u>

- For a projected state of technologies in 2035-2045.
- Ultra-low carbon renewable electricity includes wind, solar, etc.
- Does not include the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning.

In the figures featuring the bar charts, the results of the main case (indicated by the values on the bars) are based on the following key system boundaries and assumptions:

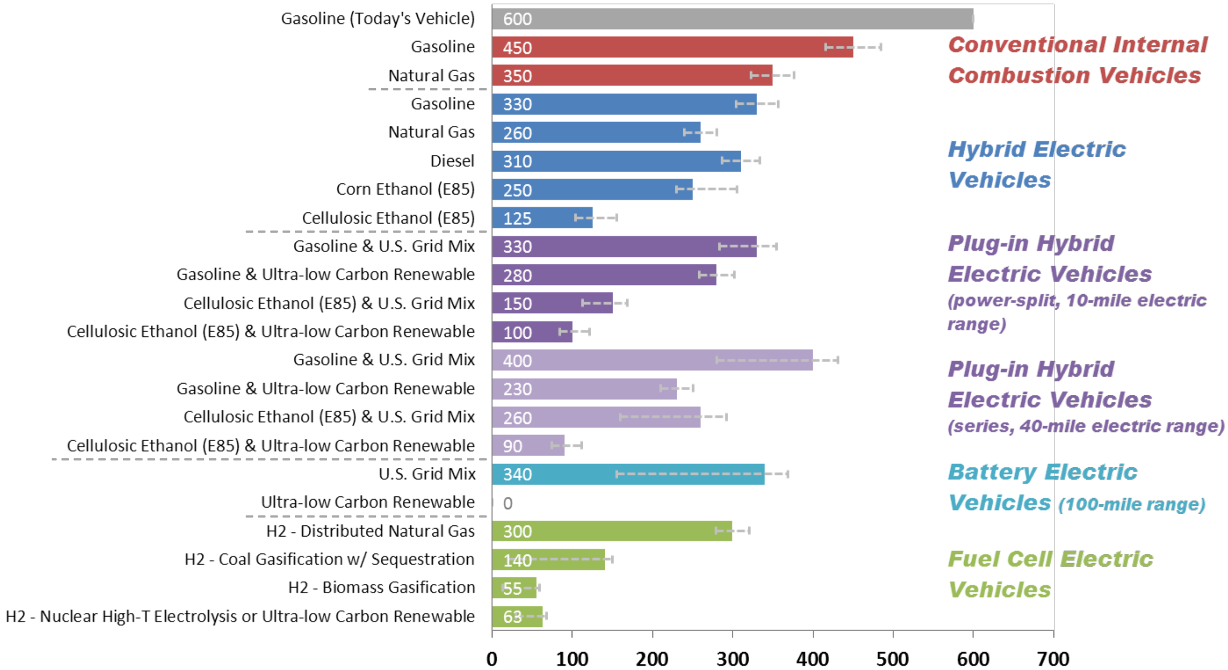
- The analysis did not include the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning.

- The carbon intensity of electricity from the average U.S. grid is based on the projection in EIA's Annual Energy Outlook 2010 for calendar year 2035, namely reduced by 11% from the current U.S. grid's carbon intensity.
- The production of corn and switchgrass as ethanol feedstock and the production of cellulosic woody crops (farmed trees) for gasification to produce hydrogen are assumed to incur no indirect land use change effect with respect to GHG emissions.
- Switchgrass ethanol plants do not benefit from the carbon credit associated with the export of excess electricity (generated with biomass residues from the ethanol production process). Similarly, hydrogen production plants using gasification technologies for coal and biomass do not benefit from the carbon credit associated with the export of excess electricity.
- Gasoline and diesel are produced from the average U.S. crude oil mix in the future (future crude oil mix is assumed to contain 18.1% of tar sands oil in the GREET model). No natural gas from shale formations is assumed. The sensitivity parameters did not include variability in the mix of crude oil or natural gas sources.
- Hydrogen produced via electrolysis with low-carbon electricity (wind and nuclear high-temperature technologies) is assumed to use EIA-projected grid electricity for hydrogen compression.
- Carbon capture and sequestration (CCS) was not assumed for hydrogen production via biomass gasification.

The low/high sensitivity bands around the values of the main case (dashed lines represent sensitivity bands) serve to illustrate uncertainties associated with projecting the performance of future vehicles and the attributes of future fuel production pathways, including the carbon intensity of electricity and other fuels, and other effects such as indirect land use change for biomass production. For example, if the carbon intensity of electricity from the U.S. grid were 50% lower than that of the EIA-projected U.S. average electricity, there would be a significant decrease in GHG emissions from plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). Similarly, if the technology for hydrogen production via coal gasification with CCS was more efficient or the excess electricity produced could be exported to displace an equivalent amount of U.S. average electricity generation, the resulting carbon credit would cause the GHG emissions of this pathway to decrease noticeably. Also, if hydrogen production in the biomass gasification pathway had the benefit of CCS, the decrease in GHG emissions would also be significant. For cellulosic ethanol, if the credit for excess electricity exported by the ethanol plant were accounted for, the carbon footprint of E85 would be approximately 10% less. The low/high bounds represented by the dashed lines show the combined effects of variations in the key parameters of the fuel production pathways and the fuel economy of the associated vehicles.

Well-to-Wheels Greenhouse Gases Emissions for Future Mid-Size SUV

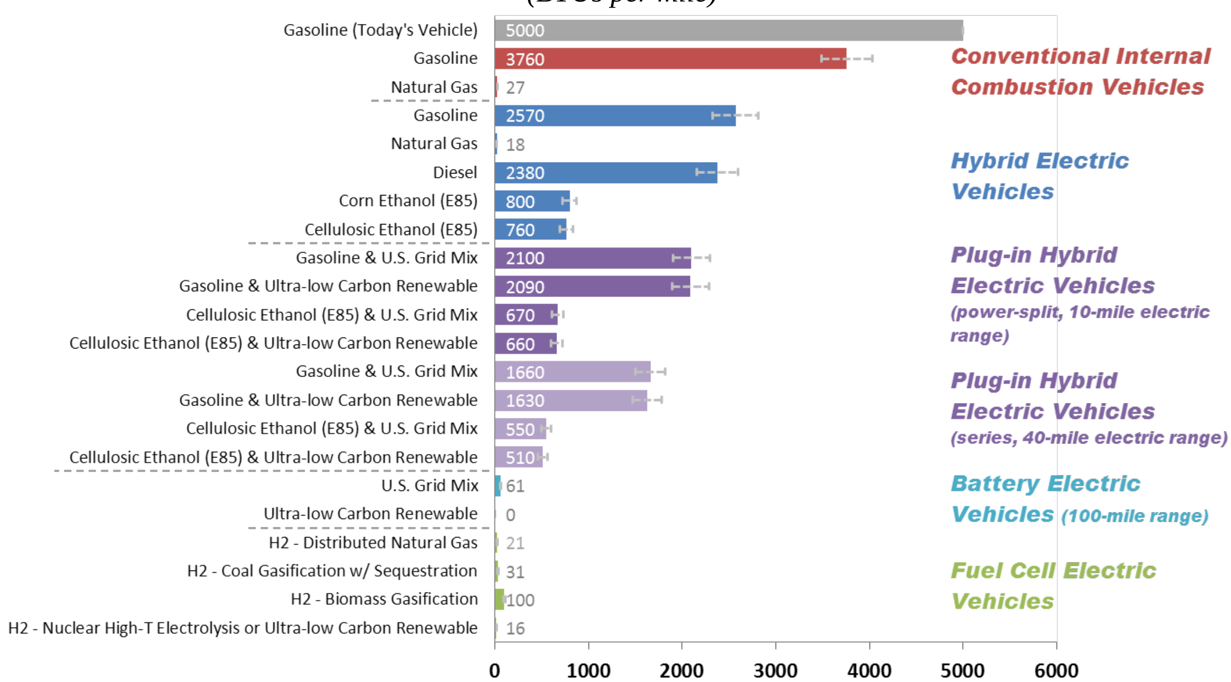
(Grams of CO_2-equivalent per mile)



Low/high band: sensitivity to uncertainties associated with projected fuel economy of vehicles and attributes of fuels pathways

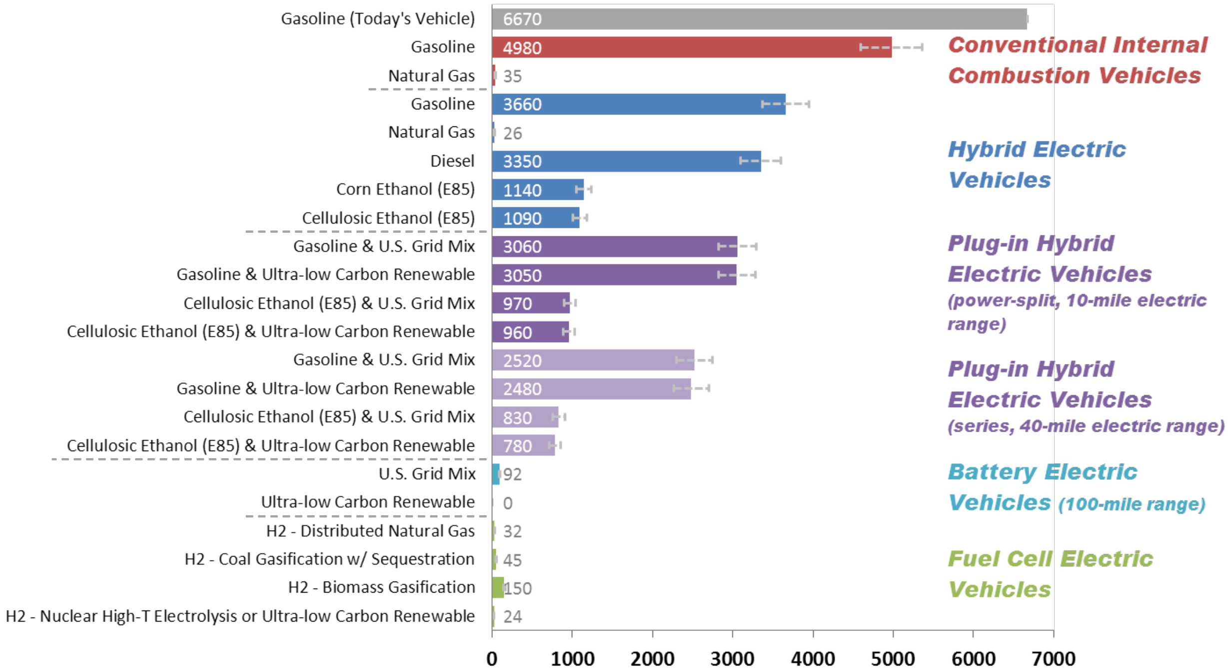
Well-to-Wheels Petroleum Energy Use for Future Mid-Size Car

(BTUs per mile)



Low/high band: sensitivity to uncertainties associated with projected fuel economy of vehicles and attributes of fuels pathways

Well-to-Wheels Petroleum Energy Use for Future Mid-Size SUV
(BTUs per mile)



Low/high band: sensitivity to uncertainties associated with projected fuel economy of vehicles and attributes of fuels pathways

Data, Assumptions, References:

- Results for all pathways are based a projected state of the technologies in 25 to 35 years, and they incorporate fuel economy improvements based on new corporate average fuel economy (CAFE) standards adopted in the Energy Independence and Security Act of 2007.
- The U.S. Environmental Protection Agency's latest method was used in deriving on-road fuel economies from results of simulations of laboratory driving tests. For more information on EPA's method, see: http://edocket.access.gpo.gov/2006/pdf/06-9749.pdf.
- Argonne National Laboratory's Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model (version 1.8c.0, March 23, 2009) was used to determine all the well-to-wheels (WTW) greenhouse gases (GHGs) and petroleum energy use estimates shown in the table below. For more information on the GREET model, see: www.transportation.anl.gov/modeling_simulation/GREET/index.html.
- Key input parameters for hydrogen production simulations were developed by National Renewable Energy Laboratory staff using the H2A hydrogen production and delivery models (version 2.01). For more information on the H2A models, see: www.hydrogen.energy.gov/h2a_analysis.html.
- The Hydrogen Macro-System Model (MSM) version 1.0 – build 1876 (developed by the National Renewable Energy Laboratory and Sandia National Laboratories) was used to guarantee consistency of assumptions between the H2A models and GREET. For more information on the MSM, see: http://www.hydrogen.energy.gov/pdfs/review10/an011_ruth_2010_o_web.pdf
- Fuel economies (as measured in the laboratory) for all fuel/vehicle systems were determined using ANL's Powertrain Systems Analysis Toolkit (PSAT Model) V6.2 SP1, Summer 2009.

For more information on the PSAT Model, see: www.transportation.anl.gov/modeling_simulation/PSAT/index.html.

- Fuel economy estimates for vehicles are based on the gallon gasoline equivalent (gge) of each applicable fuel, approximately 114,000 Btu.
- Hydrogen used in Fuel Cell Electric Vehicles is assumed to be dispensed from filling stations at 6,250 psi for 5,000-psi vehicle tank storage pressure.
- Upstream energy and emissions associated with electricity use are based on EIA's reference-case projections for the national average generation mix in 2035: 46.7% coal, 19.6% natural gas, 18.6% nuclear, 0.9% residual fuel oil, 2.4% biomass, and 11.8% other sources of renewable energy (including hydropower). These projections are derived from the *Annual Energy Outlook 2010*, which is available at: http://www.eia.doe.gov/oiaf/aeo/.
- These GHGs emissions and petroleum use results will be periodically updated to reflect changes in the assumptions and refinements to the previously mentioned models.
- Assumptions used to generate these results are based on discussions among DOE staff and the following technology analysts: Amgad Elgowainy and Michael Wang, Argonne National Laboratory, and Mark Ruth, National Renewable Energy Laboratory.

Vehicle/Fuel Pathway	Well-to-Wheels Greenhouse Gas Emissions *(grams of CO_2-equivalent/mile)* Car/SUV	Well-to-Wheels Petroleum Energy Use *(BTUs/mile) Car/SUV*	Pathway-Specific Assumptions (On-Road Fuel Economies and Other Parameters)
Future Conventional Vehicle: Gasoline -------------------- *Today's Conventional Vehicle: Gasoline*	340/450 -------------- *450/600*	3760/4980 ------------- *5000/6670*	• Fuel economies of 34 mpg (car) and 26 mpg (SUV) were used. The possible range could be 32-36 (car) and 24-28 (SUV). --- • *Fuel economies of 25 mpg (car) and 19 mpg (SUV) were used.*
Conventional Vehicle: Natural Gas	270/350	27/35	• Fuel economies of 34 mpg (car) and 26 mpg (SUV) were used. The possible range could be 32-36 (car) and 24-28 (SUV).
Hybrid-Electric Vehicle: Gasoline	235/330	2570/3660	• Fuel economies of 50 miles per gallon gasoline equivalent (mpgge) (car) and 35 mpgge (SUV) were used. The possible range could be 45-55 (car) and 32-38 (SUV).
Hybrid-Electric Vehicle: Natural Gas	185/260	18/26	• Fuel economies of 50.5 mpgge (car) and 35.3 mpgge (SUV) were used. The possible range could be 45-55 (car) and 32-38 (SUV).
Hybrid-Electric Vehicle: Diesel	220/310	2380/3350	• Fuel economies of 53 mpgge were used for the car and 35 mpgge for the SUV. The possible range for the car could be 48-58 (equal to 53-64 miles per gallon of diesel), and for the SUV could be 35-40 (equal to 38-44 miles per gallon of diesel).
Hybrid-Electric Vehicle: Corn Ethanol (E85)	180/250	800/1140	• Fuel economies of 50 mpgge (car) and 35 mpgge (SUV) were used. The possible range could be 45-55 (car) and 32-38 (SUV). • No indirect land use change was assumed for corn crops in the value of the main case shown in the bar chart. This and other

			effects (e.g, fuel economy variability) are illustrated collectively with the sensitivity bands shown as dashed lines.
Hybrid-Electric Vehicle: Cellulosic Ethanol (E85)	90/125	760/1090	• Feedstock is switchgrass [(no indirect land use change in the value of the main case shown in the bar chart; this and other effects are illustrated with the sensitivity band as dashed lines)]. • Fuel economies of 50 mpgge (car) and 35 mpgge (SUV) were used. The possible range could be 45-55 (car) and 32-38 (SUV). • Does not include reductions in *net* GHGs emissions and petroleum use that will occur through co-production and export of electricity. Surplus electricity produced in this case (and not used for internal production processes) would replace an equivalent amount of grid electricity and effectively displace associated emissions and petroleum use. The sensitivity bands illustrate this and other effects.
Plug-in Hybrid Electric Vehicle (10-mile electric range; no noticeable change in range after on-road adjustment): Gasoline	U.S. Average Grid: 230/330 Ultra-Low Carbon Electricity: 195/280	U.S. Average Grid: 2100/3060 Ultra-Low Carbon Electricity: 2090/3050	• The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] Based on PSAT simulations, a mid-sized PHEV rated with 10-mile electric range was assumed to have a on-road fuel consumption of: (1) 219 mpg (527 Btu/mile) for the car (possible range: 197-240 mpg) or 74 mpg (1543 Btu/mile) for the SUV (possible range: 69-79 mpg), and an electricity consumption of 155 mpgge (217 Wh/mile) for the car (possible range: 143-166 mpgge) or 139 mpgge (242 Wh/mile) for the SUV (possible range: 132-145 mpgge) in the blended mode of operation (primarily charge-depletion); and, (2) 50 mpg for the car (possible range: 45-54 mpg) or 35 mpg for the SUV (possible range: 32-38 mpg) in the charge-sustaining mode of operation. Electricity consumption is from the wall outlet, i.e., includes battery charging losses. • The share of distance travelled in the blended mode was assumed to be 25% of the total distance driven by these PHEVs. Note that the on-road (more realistic driving conditions) electric range remains 10 miles for the PHEV10 due to the significant assistance provided by the engine (using liquid fuel) in the blended mode of operation.
Plug-in Hybrid Electric Vehicle (10-mile electric range; no noticeable change in range after on-road adjustment): Cellulosic Ethanol (E85)	U.S. Average Grid: 105/150 Ultra-Low Carbon Electricity[2]: 70/100	U.S. Average Grid: 670/970 Ultra-Low Carbon Electricity: 660/960	• Feedstock is switchgrass [(indirect land use change effect not assumed in the value of the main case shown in the bar chart; this and other effects are illustrated with the sensitivity bands)]. • The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] PSAT simulations were performed based on the fuel and electricity consumption assumptions previously described for the gasoline PHEV. • Does not include reductions in *net* GHGs emissions and petroleum use that will occur through co-production and export of electricity. Surplus electricity produced in this case (and not used for internal production processes) would replace an equivalent amount of grid electricity and effectively displace associated emissions and petroleum use. The sensitivity bands include this and other effects. • The share of distance travelled in the blended mode was assumed to be 25% of the total distance driven by these PHEVs. Note that the on-road (more realistic driving conditions) electric range remains 10 miles for the PHEV10 due to the significant assistance provided by the engine (using liquid fuel) in the blended mode of operation.

[1] Energy use is represented here in Btu/mile, due to the complexities involved in assessing fuel economies in the charge-depletion mode in terms of miles/gallon or miles/gge. For more information on this subject, see: A. Elgowainy, et al., *Well-To-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles*, Center for Transportation Research, Argonne National Laboratory, 2010, www.transportation.anl.gov/pdfs/TA/629.pdf.

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[2] Such as solar or wind.

Plug-in Hybrid Electric Vehicle (40-mile electric range became 28-mile range after on-road adjustment): Gasoline	U.S. Average Grid: 270/400 Ultra-Low Carbon Electricity: 155/230	U.S. Average Grid: 1660/2520 Ultra-Low Carbon Electricity: 1630/2480	• The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[3] Based on PSAT simulations, a mid-sized PHEV with 40-mile all-electric range (city) was assumed to have a on-road fuel consumption of: (1) 297 mpg (388 Btu/mile) for the car (possible range: 265-327 mpg) or 164 mpg (692 Btu/mile) for the SUV (possible range: 150 -182 mpg), and an electricity consumption of 99 mpgge (337 Wh/mile) for the car (possible range: 92-107 mpgge) or 67 mpgge (500 Wh/mile) for the SUV (possible range: 63-71 mpgge) in the blended mode of operation (primarily charge-depletion); and, (2) 42 mpg for the car (possible range: 38-45 mpg) or 29 mpg for the SUV (possible range: 27-32 mpg) in the charge-sustaining mode of operation. • The share of distance travelled in the electric mode was assumed to be 51% of the total distance driven by these PHEVs. Note that the on-road (more realistic driving conditions) electric range is approximately 28 miles for the PHEV40 based on the adjustment factor of 0.70 as suggested by EPA for degrading the laboratory-based fuel economy of this and other highly efficient vehicles.
Plug-in Hybrid Electric Vehicle (40-mile electric range became 28-mile range after on-road adjustment): Cellulosic Ethanol (E85)	U.S. Average Grid: 182/260 Ultra-Low Carbon Electricity[4]: 63/90	U.S. Average Grid: 550/830 Ultra-Low Carbon Electricity: 510/780	• Feedstock is switchgrass [(indirect land use change effect not assumed in the value of the main case; this and other effects are illustrated with the sensitivity bands)]. • The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] PSAT simulations were performed based on the fuel consumption assumptions previously described for the gasoline PHEV. • Does not include reductions in *net* GHGs emissions and petroleum use that will occur through co-production and export of electricity. Surplus electricity produced in this case (and not used for internal production processes) would replace an equivalent amount of grid electricity and effectively displace associated emissions and petroleum use. The sensitivity bands include this and other effects. • The share of distance travelled in the electric mode was assumed to be 51% of the total distance driven by these PHEVs. Note that the on-road (more realistic driving conditions) electric range is approximately 28 miles for the PHEV40 based on the adjustment factor of 0.70 as suggested by EPA for degrading the laboratory-based fuel economy of this and other highly efficient vehicles.
Battery Electric Vehicle (150-mile electric range became 105 miles after on-road adjustment)	U.S. Average Grid: 230/340 Ultra-Low Carbon Electricity: 0/0	U.S. Average Grid: 61/92 Ultra-Low Carbon Electricity: 0/0	• Fuel economies of 102 mpgge (car) and 68 mpgge (SUV) were used. The possible range could be 94-112 (car) and 62-74 (SUV). • Note that the on-road (more realistic driving conditions) electric range is 105 miles for the BEV.
Fuel Cell Electric Vehicle: Hydrogen from Distributed Natural Gas	200/300	21/32	• Fuel economies of 67 mpgge (car) and 45 mpgge (SUV) were used. The possible range could be 62-73 (car) and 42-48 (SUV). • 94% energy efficiency is assumed for hydrogen compression to 6250 psi at the refueling station.

[3] Energy use is represented here in Btu/mile, due to the complexities involved in assessing fuel economies in the charge-depletion mode in terms of miles/gallon or miles/gge. For more information on this subject, see: A. Elgowainy, et al., *Well-To-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles*, Center for Transportation Research, Argonne National Laboratory, 2010, www.transportation.anl.gov/pdfs/TA/629.pdf.

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[4] Such as solar or wind.

Fuel Cell Electric Vehicle: Hydrogen from Coal Gasification with Carbon Sequestration	95/140	31/45	• Fuel economies of 67 mpgge (car) and 45 mpgge (SUV) were used. The possible range could be 62-73 (car) and 42-48 (SUV). • Hydrogen is delivered by pipeline to the refueling station in gaseous form at 300 psi. • 94% energy efficiency is assumed for hydrogen compression to 6250 psi at the refueling station. • Does not include reductions in *net* GHGs emissions and petroleum use that will occur through co-production and export of electricity. Surplus electricity produced in this case would replace an equivalent amount of grid electricity and effectively displace associated emissions and petroleum use. The sensitivity bands include this and other effects.
Fuel Cell Electric Vehicle: Hydrogen from Biomass Gasification	37/55	100/150	• Fuel economies of 67 mpgge (car) and 45 mpgge (SUV) were used. The possible range could be 62-73 (car) and 42-48 (SUV). • Feedstock is a hybrid poplar grown as a bio-energy crop. • Hydrogen is delivered by pipeline to the refueling station in gaseous form at 300 psi. • 94% energy efficiency is assumed for hydrogen compression to 6250 psi at the refueling station. • Does not include potential reductions in *net* GHGs emissions and petroleum use that will occur through co-production and export of electricity. Surplus electricity produced in this case would replace an equivalent amount of grid electricity and effectively displace associated emissions and petroleum use. The sensitivity bands include this and other effects. • Does not include additional potential reductions in GHGs emissions that are possible if CO_2 is sequestered. This and other effects (fuel economy) are illustrated with the sensitivity bands.
Fuel Cell Electric Vehicle: Hydrogen from Wind or Nuclear High-Temperature Electrolysis	42/63	16/24	• Fuel economies of 67 mpgge (car) and 45 mpgge (SUV) were used. The possible range could be 62-73 (car) and 42-48 (SUV). • Hydrogen is produced using only wind energy or nuclear-generated electricity and thermal energy—nearly all petroleum use and GHG emissions in these pathways are associated with using the U.S. average grid electricity for the delivery, storage, and dispensing of hydrogen. The sensitivity bands illustrate the combined effects of assuming a future low-carbon grid and the fuel economy variability. • 94% energy efficiency is assumed for hydrogen compression to 6250 psi at the refueling station. • Hydrogen is delivered by pipeline to the refueling station in gaseous form at 300 psi. • Electrolyzer efficiency is 74.6% based on hydrogen's lower heating value (LHV); it uses 44.7 kWh per kg of hydrogen produced.