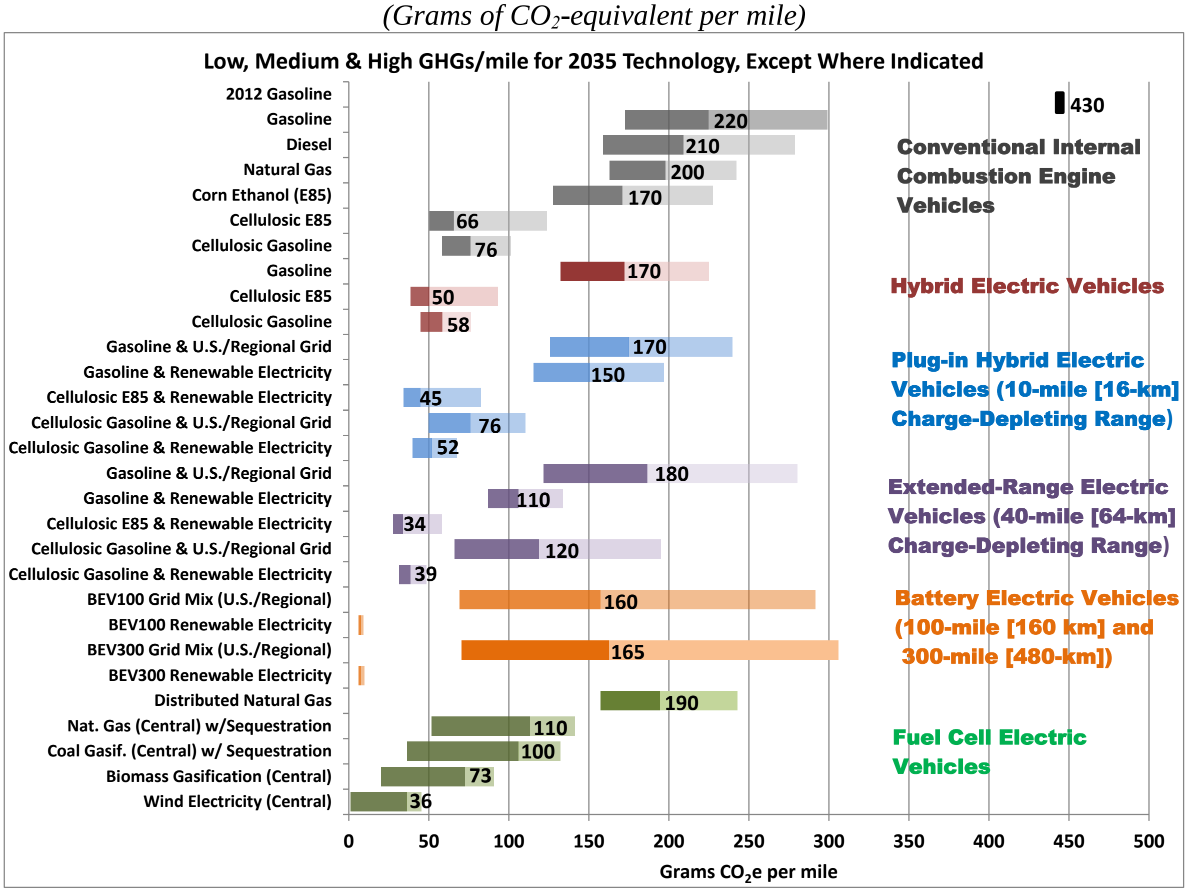
Program Record (Offices of Bioenergy Technologies, Fuel Cell Technologies & Vehicle Technologies)	
Record #: 13005 (revision #1)	**Date:** May 10, 2013
Title: Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles	
Originators: Tien Nguyen, Jake Ward & Kristen Johnson	
Approved by: Sunita Satyapal, Pat Davis, Valerie Reed **Date:** April 25, 2013 May 10, 2013	

Items:

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 a variety of fuel/vehicle pathways, for a future mid-size car and a mid-size sport utility vehicle (SUV). The results for 2035 are summarized graphically in the figures that follow.[1]

Figure 1. Well-to-Wheels Greenhouse Gases Emissions for 2035 Mid-Size Car

(Grams of CO_2-equivalent per mile)



Low/medium/high: sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.

Notes:

- *For a projected state of technologies in 2035.*
- *Renewable electricity includes biomass, hydro, wind, solar, and geothermal*

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[1] For comparison, the result for a 2012 mid-size car is also shown in the figure.

In the figures featuring the bar charts, the results of the average case are based on the following key system boundaries and assumptions:

Well-to-Wheels (WTW) Analysis

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

Electricity

- The carbon intensity[2] of electricity from the average U.S. grid is assumed to be approximately 170 g CO_2e per kBtu (580 g per kWh), based on the results from Argonne National Laboratory (ANL)'s GREET[3] model for the mix of electricity projected in EIA's Annual Energy Outlook (AEO) 2012 for calendar year 2035. (http://www.eia.gov/forecasts/archive/aeo12/tables_ref.cfm). This carbon intensity is about 8% less than the current carbon intensity.

Biofuels

- Emissions from land use change (both direct and indirect) for corn ethanol are estimated at 9.6 g CO_2e per kBtu of ethanol, based on GREET.
- The ethanol component of cellulosic E85[4] is assumed to be produced from corn stover. Emissions from land use change for corn stover are included but estimated to be minimal. Corn stover is treated as a residue by considering energy and emissions only for stover collection and transportation as well as supplemental fertilizer applications. Corn stover ethanol plants were assumed to produce excess electricity (generated with biomass residues from the ethanol production process) for sale to external users, and therefore benefit from the carbon credit associated with the grid electricity displaced by the exported electricity.
- Cellulosic gasoline is assumed to be produced via fast pyrolysis of forest residues. The analysis assumes no land use change for forest residues but does consider energy and emissions for their collection and transportation.

Natural Gas

- The analysis focuses on only the compressed natural gas (CNG) pathway[5], not other NG storage pathways such as sorbent tanks with low-pressure NG. DOE's Advanced Research Projects Agency (ARPA-E) started funding sorbent tanks projects in 2012 and technical information is not yet available to the GREET modeling team. The CNG pathway includes both conventional natural gas and shale gas (shale gas's share was at 23% in 2010 and assumed to be 49% of total natural gas in 2035, based on AEO 2012).

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[2] Carbon intensity (CI) is the amount of GHG emissions, measured on a WTW basis, per unit of energy of fuel delivered to the vehicle. GHG emissions are the sum of the CO_2 equivalent (CO_2eq) emissions of three gases, CO_2, CH_4, and N_2O, weighted by their 100-year global warming potentials from the International Panel on Climate Control (IPCC). In this document, CI is expressed in g CO_2eq/kBtu.

[3] The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation model (greet.es.anl.gov).

[4] E85 is a gasoline-ethanol blend that contains approximately 50% to 85% ethanol and can be used in flexible fuel vehicles. The GHG and energy use results reported here for E85 assume a 19% gasoline and 81% ethanol content.

[5] The 2012 GREET model uses EPA's updated (as of 2011) estimation of U.S. CH_4 emissions (significant increase from previous estimate). This change was necessary because CH_4 has a global warming potential of 25 (i.e., relative to CO_2). On a WTW basis, GREET shows that CH_4 accounts for approximately 17% of a natural gas vehicle's WTW GHG emissions, most of which occurs during gas well drilling, gas extraction, processing, and distribution.

Gasoline and Diesel

- Gasoline and diesel are produced from the average U.S. crude oil mix in the future (future crude oil mix is assumed to contain 16% of oil sands in the GREET model). U.S. gasoline is primarily E10 (with 10% ethanol by volume) and therefore this assumption was made for the analysis.

Hydrogen

- Hydrogen produced at central plants via electrolysis with wind electricity is assumed to use EIA-projected grid electricity (i.e., the average mix for the U.S.) for pipeline delivery of hydrogen and hydrogen compression at the refueling station.
- The feedstock for hydrogen produced from biomass gasification is assumed to be short-rotation woody crops. GREET does not currently include land use change effects with respect to GHG emissions for this feedstock[6]. This assumption will be monitored in future releases of this record as more information becomes available. Hydrogen production plants using gasification technologies for coal and biomass were not assumed to produce excess electricity for sale to external users. Pipeline delivery and compression at the refueling station are assumed to use U.S. grid electricity.
- Carbon capture and sequestration (CCS) is assumed for central hydrogen production from natural gas and coal, but is not assumed for hydrogen via biomass gasification.

The low/medium/high values serve to illustrate uncertainties associated with projecting the performance of future vehicles and a number of selected attributes of future fuel production pathways, including the carbon intensity of electricity and other fuels, and other effects such as credit for electricity sales to external users. For example:

- To illustrate the effect of electricity's carbon intensity on plug-in vehicles, the U.S. national average, California and Illinois grids (Year 2035 from AEO 2012) were used.
- For cellulosic ethanol, using biomass residues for electricity generation results in an electricity credit. If the credit for excess electricity exported by the ethanol plant were not accounted for, the carbon footprint of E85 would be approximately 40% higher (assuming the EIA-projected grid electricity in 2035). Credits for other potential products made from biomass residues are not included but will be considered as additional data become available.

The low/high values represented by the bars in the following figure show the combined effects of variations in selected parameters of certain fuel production pathways and the fuel economy of the associated vehicles.

[6] Current literature suggests that land use change for woody crops may be minimal.

Figure 2. Well-to-Wheels Greenhouse Gases Emissions for 2035 Mid-Size SUV
(Grams of CO_2-equivalent per mile)

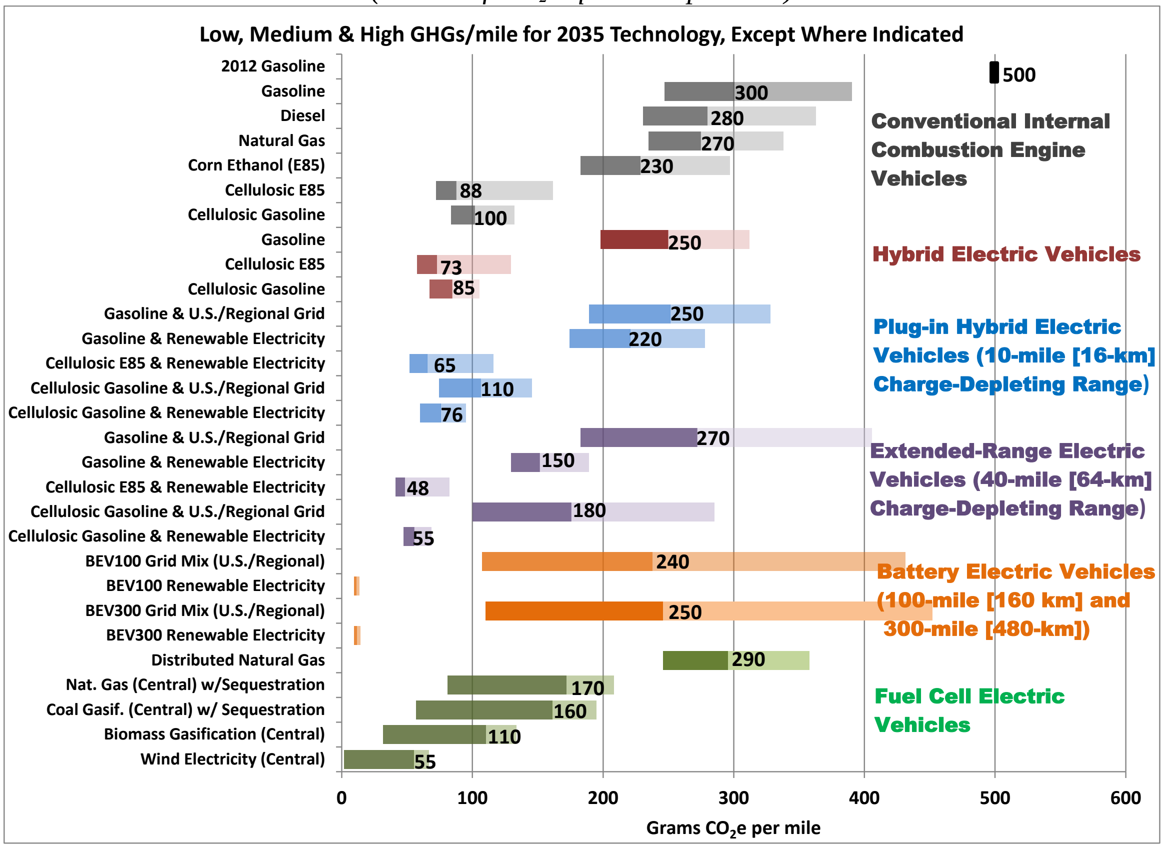


Figure 3. Well-to-Wheels Petroleum Energy Use for 2035 Mid-Size Car *(BTUs per mile)*

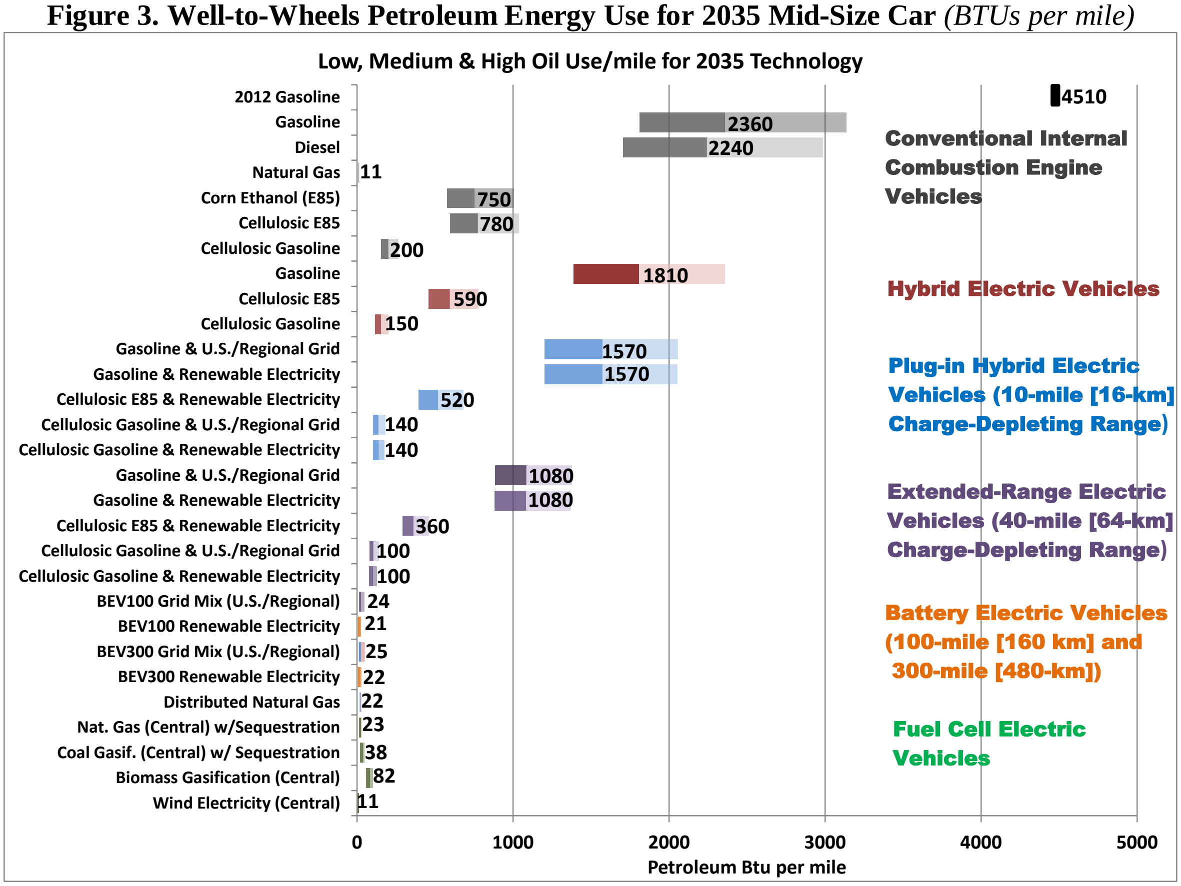
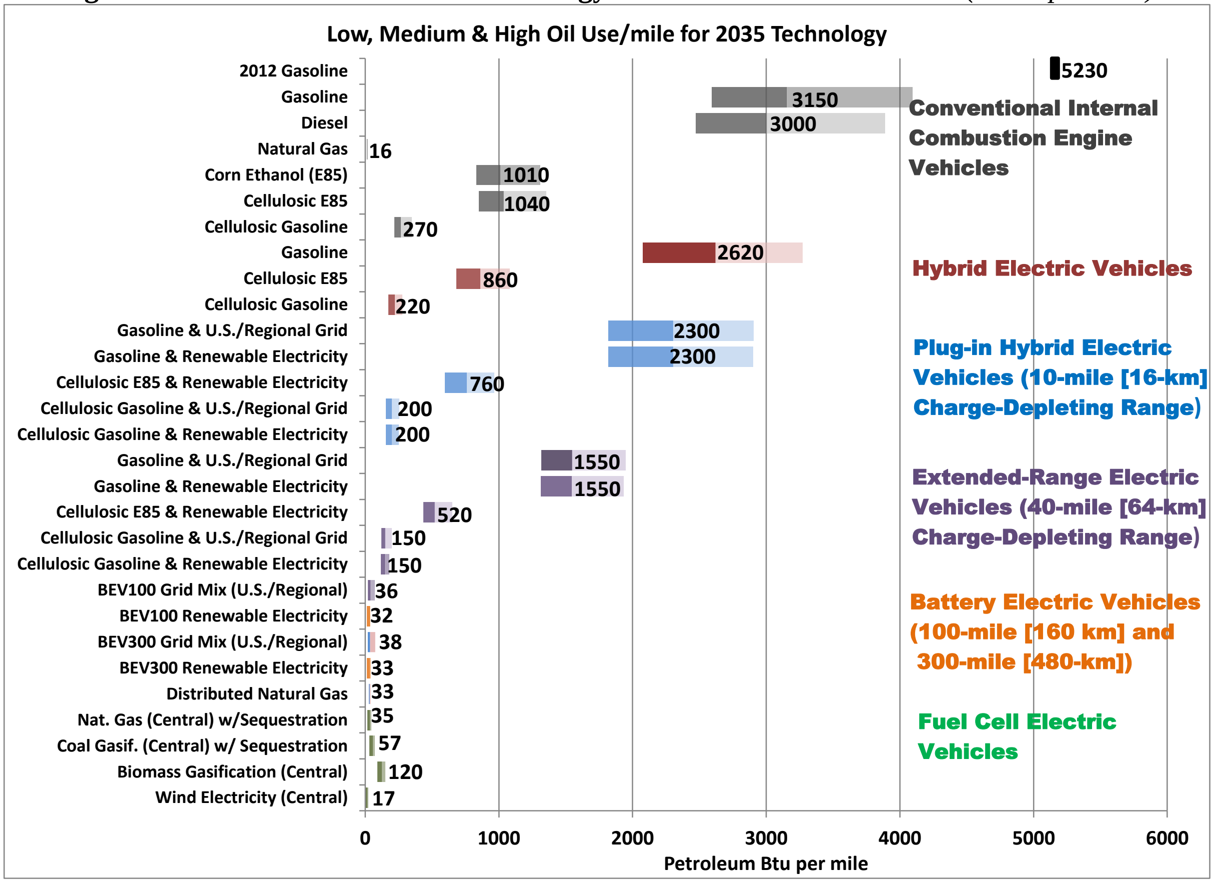


Figure 4. Well-to-Wheels Petroleum Energy Use for 2035 Mid-Size SUV *(BTUs per mile)*



Data, Assumptions, References:

- Fuel economies for all fuel/vehicle systems were determined using ANL's Autonomie modeling system, a vehicle simulation software system used to assess the fuel consumption and performance of advanced vehicles. For information on Autonomie, see: http://www.transportation.anl.gov/modeling_simulation/PSAT/autonomie.html. The U.S. Environmental Protection Agency's latest method was used by the modelers in deriving on-road fuel economies from results of simulations of laboratory driving tests. For information on EPA's method, see: http://www.gpo.gov/fdsys/pkg/FR-2009-11-25/pdf/E9-27945.pdf and http://www.smidgeindustriesltd.com/leaf/EPA/EPA_test_procedure_for_EVs-PHEVs-1-13-2011.pdf.
- GREET (December 2012 version at greet.es.anl.gov) was used to determine the WTW GHG emissions and petroleum energy use. The FCEV analysis involved the use of GREET, the Hydrogen Macro-System Model (MSM) and hydrogen production models from the H2A suite of models[7] (Version 3 issued in Spring 2012).

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[7] GREET is designed to be a self-standing capability once it has been updated with current results from H2A production models (updating GREET with new results from H2A delivery models has been relatively quick because ANL staff is responsible for both GREET and delivery models). When this work was performed, the updating of GREET with new results from H2A production models was still ongoing and therefore MSM was exercised to ensure consistency between these and GREET. MSM was developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (http://h2-msm.ca.sandia.gov/).

- Fuel economy estimates for vehicles are based on the gallon gasoline equivalent (gge) of each applicable fuel, approximately 115,000 Btu per gallon of gasoline (lower heating value).
- Hydrogen used in FCEVs is assumed to be dispensed from filling stations at 12,650 psi for 10,000-psi vehicle tank storage pressure.
- These results for GHG emissions and petroleum use will be periodically updated to reflect changes in the assumptions and refinements to the previously mentioned models.

The grid mixes used in this analysis are shown below.

Electricity Shares by Fuel in 2035	**U.S. Average**	**California (Lower in Carbon)**	**Illinois (Higher in Carbon)**
Coal	39.9%	3.72%	77.2%
Pulverized coal	*39.7%*	*3.72%*	*77.2%*
IGCC	*0.27%*	0%	*0%*
Petroleum	0.61%	0.23%	0.22%
Natural Gas	26.1%	46.6%	3.30%
Steam turbine	*1.44%*	*1.86%*	*0.00%*
Combustion turbine	0.69%	*2.84%*	*0.22%*
Combined cycle	23.9%	41.9%	*3.08%*
Nuclear Power	19.3%	10.7%	13.3%
Biomass & Municipal Waste	1.39%	1.26%	0.63%
Rest of Renewable Sources	12.7%	37.5%	5.32%
Conventional Hydropower	*6.75%*	*10.8%*	*2.69%*
Geothermal	*1.01%*	*11.4%*	*0.00%*
Wind	*4.19%*	*9.41%*	2.62%
Solar	*0.73%*	*5.89%*	*0.00%*

Table 1. Electric Generation Mixes in 2035: U.S. Grid, California and Illinois (derived from published AEO 2012 and additional renewable generation results provided by EIA staff)

Table 2 lists the GHG emissions and petroleum consumption per mile driven for the medium-optimism[8] mid-size car and SUV. The right-hand column summarizes the fuel economy assumptions for the medium-optimism case along with possible ranges that bound the uncertainties associated with achieving these targets (only on-road fuel economy numbers are shown, i.e., using EPA-suggested methodologies for adjusting the dynamometer test results to account for realistic driving behavior, including the use of air conditioning, frequency of acceleration, etc.). The right-hand column also lists the assumptions associated with the carbon and petroleum intensities of the different fuels considered in this analysis. The effects of the variability in fuel economy and scenario-specific assumptions (such as the carbon intensity of electricity and the effect of excess electricity sales for the cellulosic ethanol pathway) are illustrated in the charts.

[8] The Vehicle Technologies Office has three sets of potential R&D outcomes for LDV technologies (mid-range, more optimistic and less optimistic)

Table 2. Assumptions and Detailed Results for 2035 Technologies

Vehicle/Fuel System Pathway	WTW GHG (grams of CO2e/mile) & *Petroleum Energy Use (BTUs/mile)* Car/SUV	Carbon Intensity of Electricity & Other Fuels (grams of CO2e/kBtu)	Pathway Assumptions (On-Road Fuel Economies and Other Parameters)
Conventional Internal Combustion Engine Vehicles:			The effects of fuel economy variability are shown with the sensitivity bars. For E85 with cellulosic ethanol, an additional sensitivity was reflected in the sensitivity bars. For CNG LDVs, GREET's data shows that the carbon intensity of shale gas is similar to that of conventional NG.
Conventional Vehicle: Gasoline (E10, with 10% ethanol by volume) ------------------------------ Today's Conventional Vehicle (E10)	**GHG**: 220 (Car) / 300 (SUV) ***Petroleum**:* *2360 (Car) /* *3150 (SUV)* -------------------------- 430/500 *4510/5230*	Carbon intensity (CI) of fuel: 96 --------------------- CI of fuel: 96	Fuel economies of 49 mpgge (car) and 37 mpgge (SUV) were used. The possible range could be 37-64 (car) and 28-45 (SUV). *Note: with 2035 sales at 64% for cars and 36% for light trucks (AEO 2012), the weighted average fuel economy for new ICEVs in 2035 is 44 mpgge (range: 33-55).* --- 26 mpgge (car) and 22 mpgge (SUV). *Weighted average of cars & SUVs:24 mpgge*
Conventional Vehicle: Diesel	210/280 *2240/3000*	CI of fuel: 100	55 mpgge (car) and 41 mpgge (SUV). Range: 41-72 (car) and 32-50 (SUV). *Weighted average of cars & SUVs: 49 (37-62)*
Conventional Vehicle: Corn Ethanol (E85)	170/230 *750/1010*	CI of fuel: 73	Same fuel economy as gasoline LDVs, i.e., 37-64 (car) and 28-45 (SUV). Indirect land use change was assumed for corn crops in the value of the main case shown in the bar chart. Fuel economy variability effects are illustrated with sensitivity bars.
Conventional Vehicle: Cellulosic Ethanol (E85)	66/88 *780/1040*	CI of fuel: 28	Same fuel economy as gasoline LDVs. Includes reductions in *net* GHG emissions and petroleum use that will occur through co-production and export of electricity. Surplus electricity (not used for production processes) would replace grid electricity, displacing GHG emissions.
Conventional Vehicle: Cellulosic Gasoline	76/100 *200/270*	CI of fuel: 33	Same fuel economy as gasoline LDVs.
Conventional Vehicle: CNG	200/270 *12/17*	CI of fuel: 85	49 mpgge (car) and 37 mpgge (SUV). Range: 40-58 (car) and 29-41 (SUV). *Weighted average of cars & SUVs: 43 (35-51).*
Hybrid-Electric Vehicles:			Fuel economies of 64 mpgge (car) and 44 mpgge (SUV) were used (range: 49-83 - car and 35-56 - SUV). *Weighted average of cars & SUVs: 55 (43-71).* Sensitivity bars in the chart are based on the approach used for conventional LDVs.
Gasoline (E10)	170/250 *1810/2620*	CI of fuel: 96	
Cellulosic Ethanol (E85)	50/73 *590/860*	CI of fuel: 28	Same WTW assumptions as described in the bullets on this biofuel for the conventional vehicle.

Cellulosic Gasoline	58/85 *150/220*	CI of fuel: 33	Same WTW assumptions as described in the bullets on this biofuel for the conventional vehicle.
Plug-in Hybrid Electric Vehicle with 10-mile charge depleting (CD) range: The share of distance travelled in the blended mode was assumed to be 25% of the total distance driven by these PHEVs. The on-road (more realistic driving conditions) CD 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.			A mid-size PHEV rated with 10-mile blended CD range was assumed to have an on-road fuel consumption of: (1) 183 mpgge for the car (range: 135-240) or 102 mpgge for the SUV (75-139), and an electricity consumption of 180 Wh/mile for the car (152-202) or 230 Wh/mile for the SUV (218-237) in the blended mode of operation (primarily charge-depleting); and, (2) 63 mpgge for the car (48-82) or 44 mpgge for the SUV (35-55) in the charge-sustaining (CS) mode.[9] Combined electric & non-electric fuel economy: Car - 68 mpgge (range: 53-88); SUV - 47 mpgge (range: 38-59). *Weighted average of cars & SUVs: 58 (46-74).* Electricity consumption is from the battery, not the wall outlet, i.e., does not include battery and charging losses. These account for an additional 2%-8% reduction in efficiency (2035 technology).
PHEV10 – Non-Electric Fuel	**PHEV10 - Electricity**		The effects of fuel economy variability are illustrated with the sensitivity bars.
Gasoline (E10): CI is 96	U.S. Grid: 170/250 *1570/2300* Renewable Electricity[10]: 150/220 *1570/2300*	CI of electricity: U.S. Grid: 170 California: 91 Illinois: 257 Renewable Electricity: 8	In addition to fuel economy variability, the effect of regional variation in the carbon intensity of electricity is illustrated using California and Illinois (low to high emissions per mile).
Cellulosic Ethanol (E85): CI is 28	Renewable Electricity: 45/65 *520/760*	CI of electricity: Renewable Electricity: 8	Same WTW assumptions as described in the bullets on this biofuel for the conventional vehicles.
Cellulosic Gasoline: CI is 33	U.S. Grid: 76/105 *140/200* Renewable Electricity: 52/76 *140/200*	CI of electricity: U.S. Grid: 170 California: 91 Illinois: 257 Renewable Electricity: 8	Same WTW assumptions as described in the bullet on this biofuel for the conventional vehicles. For electricity: regional variation in the carbon intensity of electricity is illustrated as previously described.

[9] For more information on the approach for analyzing electric drives, 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.

[10] Primarily hydropower, wind, solar, biopower and geothermal.

Extended-Range Electric Vehicle with 40-mile charge depleting (CD) range: The share of distance travelled in the CD mode was assumed to be 50% of the total distance driven by these EREVs. The on-road (more realistic driving conditions) CD range is approximately 28 miles for the EREV40, based on the adjustment factor of 0.70 suggested by EPA for degrading the laboratory-based fuel economy of this and other highly efficient vehicles. The engine (using liquid fuel) is not activated during the EREV's CD mode of operation.			A mid-size EREV with 40-mile CD range (city) was assumed to have an on-road electricity consumption of 271 Wh/mile for the car (range: 232-311) or 406 Wh/mile for the SUV (356-459) in CD; and, (2) 53 mpgge for the car (42-65) or 37 mpgge for the SUV (30-43) in CS.[11] Combined electric & non-electric fuel economy: Car -74 mpgge (range: 60-89), SUV – 51 mpgge (range: 42-59). *Weighted average of cars & SUVs: 63 (52-75).* Electricity consumption simulated with Autonomie is from the battery, not the wall outlet, i.e., does not include battery and charging losses. These account for an additional 2%-8% reduction in efficiency (2035 technology).
EREV40 - Non-Electric Fuel	**EREV40 - Electricity**		
Gasoline (E10): CI is 96	U.S. Grid: 180/270 *1080/1550* Renewable Electricity: 110/150 *1080/1550*	CI of electricity: U.S. Grid: 170 California: 91 Illinois: 257 Renewable Electricity: 8	In addition to fuel economy variability, the effect of regional variation in electricity's carbon intensity is illustrated using California and Illinois.
Cellulosic Ethanol (E85): CI is 28	Renewable Electricity: 34/48 *360/520*	CI of electricity: Renewable Electricity: 8	Same WTW assumptions as those described in the bullets on this biofuel for the conventional vehicles.
Cellulosic Gasoline: CI is 33	U.S. Grid: 120/180 *95/130* Renewable Electricity: 39/55 *100/150*	CI of electricity: U.S. Grid: 170 California: 91 Illinois: 257 Renewable Electricity: 8	Same WTW assumptions as those described in the bullets on this biofuel for the conventional vehicles. In addition to fuel economy variability, the effect of regional variation in the carbon intensity of electricity is illustrated as previously described.

[11] For more information on PHEV analysis, 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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Battery Electric Vehicles:			Electricity consumption does not include battery and charging losses. The effects of fuel economy variability and electricity's carbon intensity are illustrated with the sensitivity bars in the figure.
Battery Electric Vehicle (100-mile electric range became 70 miles after on-road adjustment)	U.S. Grid: 160/240 *24/36* Renewable Electricity: 7/11 *21/32*	CI of electricity: U.S. Grid: 170 California: 91 Illinois: 257 Renewable Electricity: 8	Fuel economies of 260 Wh/mile (car) and 390 Wh/mile (SUV) were used (210-300 - car and 330-450 - SUV). *Weighted average of cars & SUVs: 305 (260-360).*
Battery Electric Vehicle (300-mile electric range became 210 miles after on-road adjustment)	U.S. Grid: 165/250 *25/38* Renewable Electricity: 8/12 *22/33*	CI of electricity: U.S. Grid: 170 California: 91 Illinois: 257 Renewable Electricity: 8	265 Wh/mile (car) and 400 Wh/mile (SUV). Range: 220-320 (car) and 340-470 (SUV). *Weighted average of cars & SUVs: 315 (265-375).* See statement re. grid electricity for the BEV100: the same was applied here.
Fuel Cell Electric Vehicles:			Fuel economies of 79 mpgge (car) and 52 mpgge (SUV) were used (63-98 - car and 43-63 - SUV). *Weighted average of cars & SUVs: 67 (54-81).* 90.2% energy efficiency is assumed for H_2 compression to 12,700 psi at the retail station. H_2 from central production plants is delivered by pipeline to the station in gaseous form at 300 psi. Grid electricity is used for pipeline delivery of H_2 and storage and dispensing at the fueling station. The effects of fuel economy variability are illustrated with sensitivity bars.
Refueling Station: Distributed Natural Gas	190/290 *22/33*	CI of fuel: 134	Sensitivity includes the effects of fuel economy variability.
Central Plant: Natural Gas Reforming with Carbon Sequestration	110/170 *23/35*	CI of fuel: 78	Sensitivity includes fuel economy variability and the assumption of a renewable grid whose electricity could be used for delivery and dispensing (CI of H_2 reduced to approximately 43).
Central Plant: Coal Gasification with Carbon Sequestration	100/160 *38/57*	CI of fuel: 73	Sensitivity includes the parameters described above (CI of H_2 reduced to approximately 30).
Central Plant: Biomass Gasification	73/110 *82/120*	CI of fuel: 50	Feedstock is a short-rotation woody crop (hybrid poplar). Sensitivity includes the parameters described above (CI of H_2 reduced to 16).
Central Plant: Wind for H_2 production and grid electricity for delivery, storage and dispensing	36/55 *11/17*	CI of fuel: 25	Electrolyzer efficiency is 74.6% based on H_2's lower heating value (LHV); it uses 44.7 kWh per kg of H_2 produced. Sensitivity includes the parameters described above (CI of H_2 reduced to virtually 0).