Program Record (Offices of Bioenergy Technologies, Fuel Cell Technologies & Vehicle Technologies)	
Record #: 16008	**Date:** December 22, 2016
Title: Life-Cycle Greenhouse Gas Emissions and Petroleum Use for Mid-Size Cars	
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Item

This updated analysis shows the following results for light-duty vehicles (LDVs) potentially deployed in the 2035 timeframe:

- Future LDVs could have significantly lower per-mile emission of greenhouse gases (GHGs) and consumption of petroleum than today's conventional gasoline car at 450 grams of CO_2 equivalent (CO_2e) per mile, with petroleum-fueled cars (conventional internal combustion engine vehicles or ICEVs) at 240–340 grams per mile; petroleum-fueled hybrid electric vehicles (HEVs) at 170–230; 10-mile range (on batteries) plug-in hybrid electric vehicles (PHEV10) at 170–230 (using U.S. grid electricity and petroleum fuels); 35-mile range extended-range electric vehicles (EREV35) at 120–260 (using U.S. grid electricity and petroleum fuels); battery electric vehicles (BEVs) at 100–270 (using U.S. grid electricity and petroleum); and fuel cell electric vehicles (FCEVs) at 170–260 when using natural gas-derived hydrogen.
- Low-carbon fuels (including electricity) could help achieve significant, additional reduction in GHG emissions for all the power trains, e.g., 100–125 grams per mile for conventional ICEVs on cellulosic gasoline, 54–65 for EREVs on cellulosic gasoline and renewable electricity, 33–44 for BEVs on renewable electricity, and 48–80 for FCEVs on hydrogen from renewable electricity.

Introduction

DOE is pursuing a portfolio of technologies with the potential to significantly reduce greenhouse gas (GHG) emissions and petroleum consumption. This record documents the assumptions and results of analyses conducted to estimate the life-cycle GHG emissions and petroleum energy use resulting from a variety of vehicle-fuel pathways, for a generic mid-size car (2035 model year). In the figures and tables that follow, results include GHG emissions and petroleum use.

Discussion

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

Life-Cycle Analysis

- The analysis included the fuel cycle and the life-cycle effects of vehicle manufacturing as well as recycling and disposal of vehicle material (assuming no replacement for major components, e.g., fuel cell, compressed tanks, motors, batteries other than two lead acid battery replacements[1] over vehicle lifetime). These assumptions may change as knowledge of performance of these components develops over time. The carbon and petroleum intensities (from Argonne National Laboratory's GREET1 and GREET2[2] models) do not include infrastructure construction and decommissioning. The vehicle lifetime mileage is estimated at 178,000 miles.[3]

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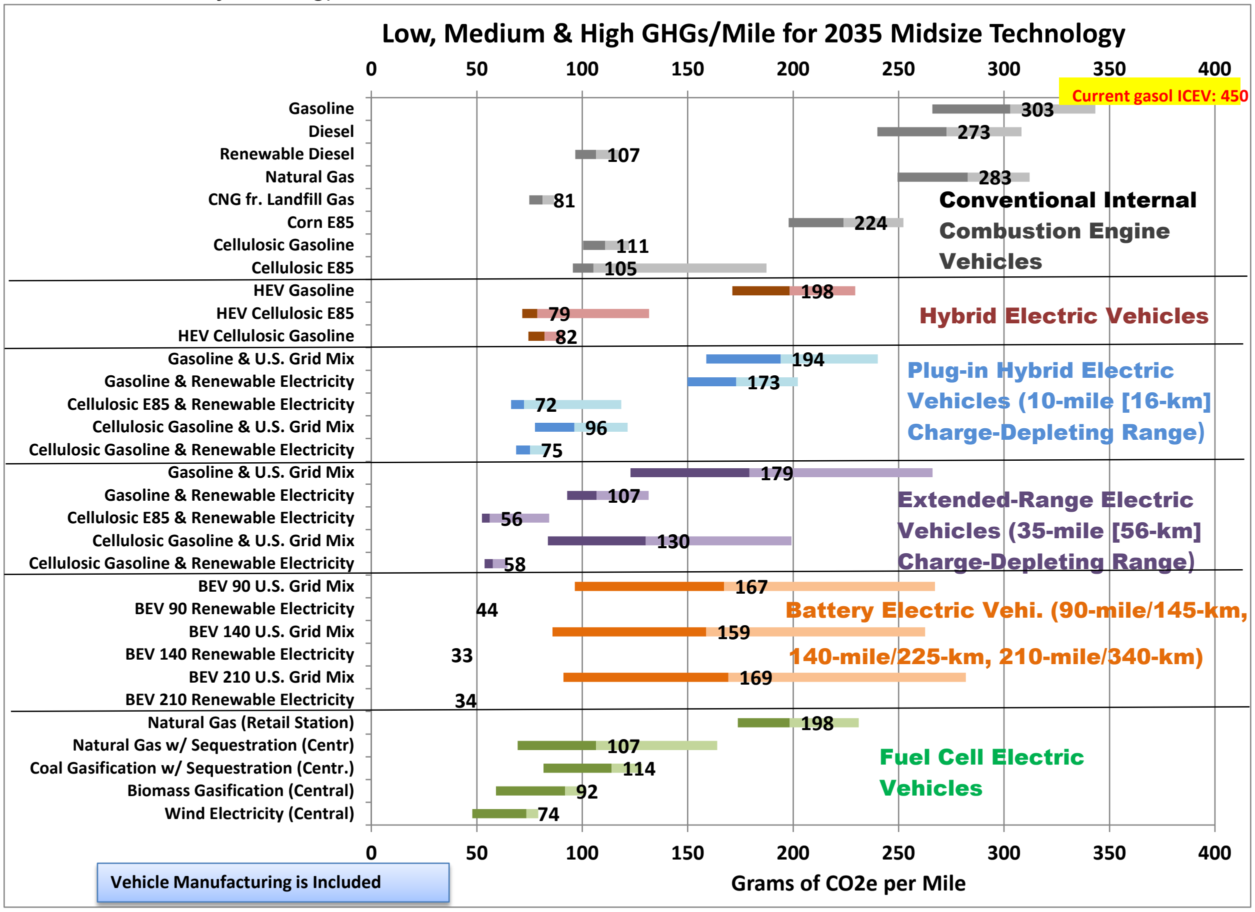
[1] Automakers continue to use the 12-volt lead acid battery for running the lights and entertainment system even for plug-in and fuel cell electric vehicles.

[2] The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation model (https://greet.es.anl.gov), 2015: includes two components: GREET1 for well-to-wheels analysis of fuels production and vehicle operation, and GREET2 (vehicle cycle model) for vehicle production, disposal, and recycling. GREET default assumptions were used, unless otherwise noted (see documentation at https://greet.es.anl.gov/publication-ycrv02rp).

[3] This analysis assumed 178,000-mile vehicle lifetimes, based on the National Highway Traffic Safety

Figure 1. Life-Cycle Greenhouse Gas Emissions for 2035 Mid-Size Car *(grams of CO_2-equivalent per mile with vehicle manufacturing)*



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

For vehicles running on carbonless fuels, all emissions are from the vehicle cycle, i.e., vehicle manufacturing, recycling, and disposal. These emissions are not a function of fuel economy. In this analysis the carbon intensity of energy used in the vehicle cycle from the GREET model was not varied, resulting in point estimates (no high/low range) for BEVs on renewable electricity.

Electricity

The 2035 electric grid mixes used in this analysis are shown below.

Table 1. Electric Generation Mixes in 2035: U.S. Grid, California and Illinois (derived from AEO 2015)

Electricity Shares by Fuel in 2035	U.S. Average	California	Illinois
Coal	35%	0.4%	71%
Petroleum	0.5%	0%	0.3%
Natural Gas	30%	54%	8.5%
Nuclear Power	17%	5.6%	13%
Renewable Sources & Other	17.5%	40%	7.2%

Administration's information: 14,231 miles in 1st year, decreasing annually to 9,249 miles in 15th year (Table 5 in http://www-nrd.nhtsa.dot.gov/Pubs/809952.PDF). BEV90 lifetime mileage was assumed to be 125,000. Plug-in and fuel cell cars are relatively recent and it is not clear if the same lifetime mileage should be assumed for them. This assumption may change as more is known with time.

- The carbon intensity[4] of electricity from the average U.S. grid available at end use is assumed to be approximately 150 g CO_2e per kBtu (510 g per kWh), based on the results from Argonne National Laboratory (ANL)'s GREET1 model for the mix of electricity projected in EIA's Annual Energy Outlook (AEO) 2015 for 2035 (http://www.eia.gov/forecasts/aeo/tables_ref.cfm). This carbon intensity is about 9% less than that of the current (2015) U.S. grid mix.
- Carbonless electricity was assumed for vehicle operation under certain scenarios (but average U.S. grid electricity was assumed for manufacturing and distributed use, e.g., hydrogen compression at refueling stations, even under such renewable electricity scenarios).

Biofuels

- Emissions from land use change (both direct and indirect) for corn ethanol are estimated at approximately 8 g CO_2e per kBtu of ethanol, based on GREET1 calculations.
- Renewable diesel is assumed to be produced from the pyrolysis of forest residues.
- The ethanol component of cellulosic E85[5] is assumed to be produced from corn stover fermentation. 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 export to U.S. grid, and therefore this pathway benefits from the carbon credit associated with the average grid electricity being 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 and Landfill Gas

- The compressed natural gas (CNG) pathway includes both conventional natural gas and shale gas (in GREET, the carbon intensity of shale gas is similar to that of conventional natural gas).

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 12% of oil sands when running GREET1, versus currently 10% as EIA reported.[6]

Hydrogen

- The feedstock for hydrogen produced from biomass gasification is assumed to be short-rotation woody crops. Current GREET1 version does not currently include land use change GHG effects for this feedstock.[7] This assumption will be updated 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 export to U.S. grid. Pipeline delivery and compression at the refueling station are assumed to use U.S. average grid electricity.
- Carbon capture and sequestration (CCS) is assumed for central hydrogen production from natural gas and coal, but is not assumed for hydrogen production via biomass gasification or at refueling stations via natural gas steam methane reforming.

[4] Carbon intensity (CI) is the amount of GHG emissions on a life-cycle basis per unit of fuel energy to the vehicle. GHG emissions are the sum of the CO_2 equivalent (CO_2e) emissions of CO_2, CH_4, and N_2O, weighted by their 100-year global warming potentials from the Intergovernmental Panel on Climate Change (IPCC).

[5] 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 17% gasoline and 83% ethanol content by volume.

[6] https://www.eia.gov/tools/faqs/faq.cfm?id=727&t=6
https://www.eia.gov/opendata/qb.cfm?sdid=PET.MTTIMUSCA1.M

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

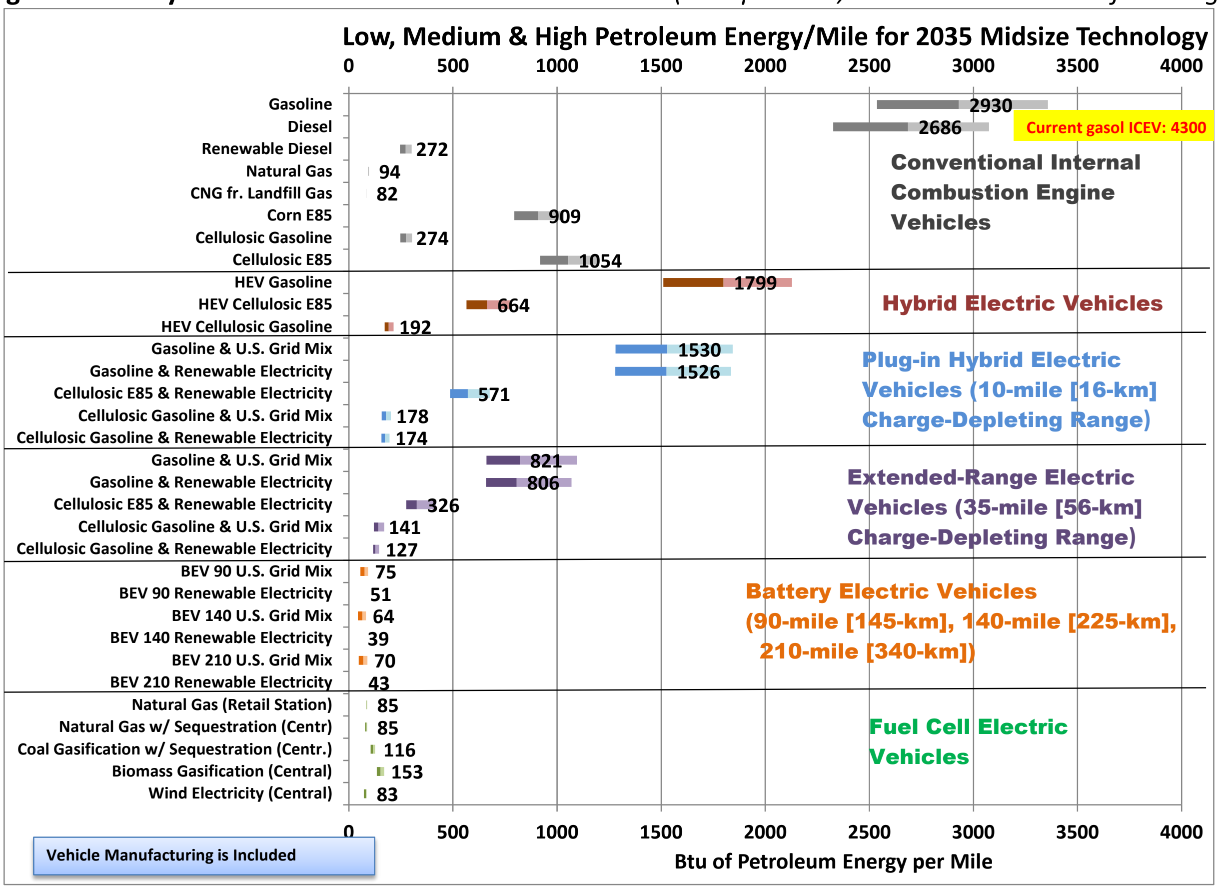
Sensitivity Cases

The low/medium/high values serve to illustrate variability and uncertainty 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 export to U.S. grid. 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 2015) were evaluated.
- For cellulosic ethanol, using biomass residues for electricity generation and export results in a GHG emissions credit. If the credit for excess electricity exported by the ethanol plant were not accounted for, the carbon footprint of E85 would be approximately 30% higher (assuming electricity export to displace the EIA-projected grid electricity in 2035). Credits for other potential products made from biomass residues are not included but will be considered in future revisions of this record as additional data become available.

The low/high values represented by the bars in Figure 2 show the combined effects of variations in selected parameters of certain fuel production pathways and the fuel economy of the associated vehicles.

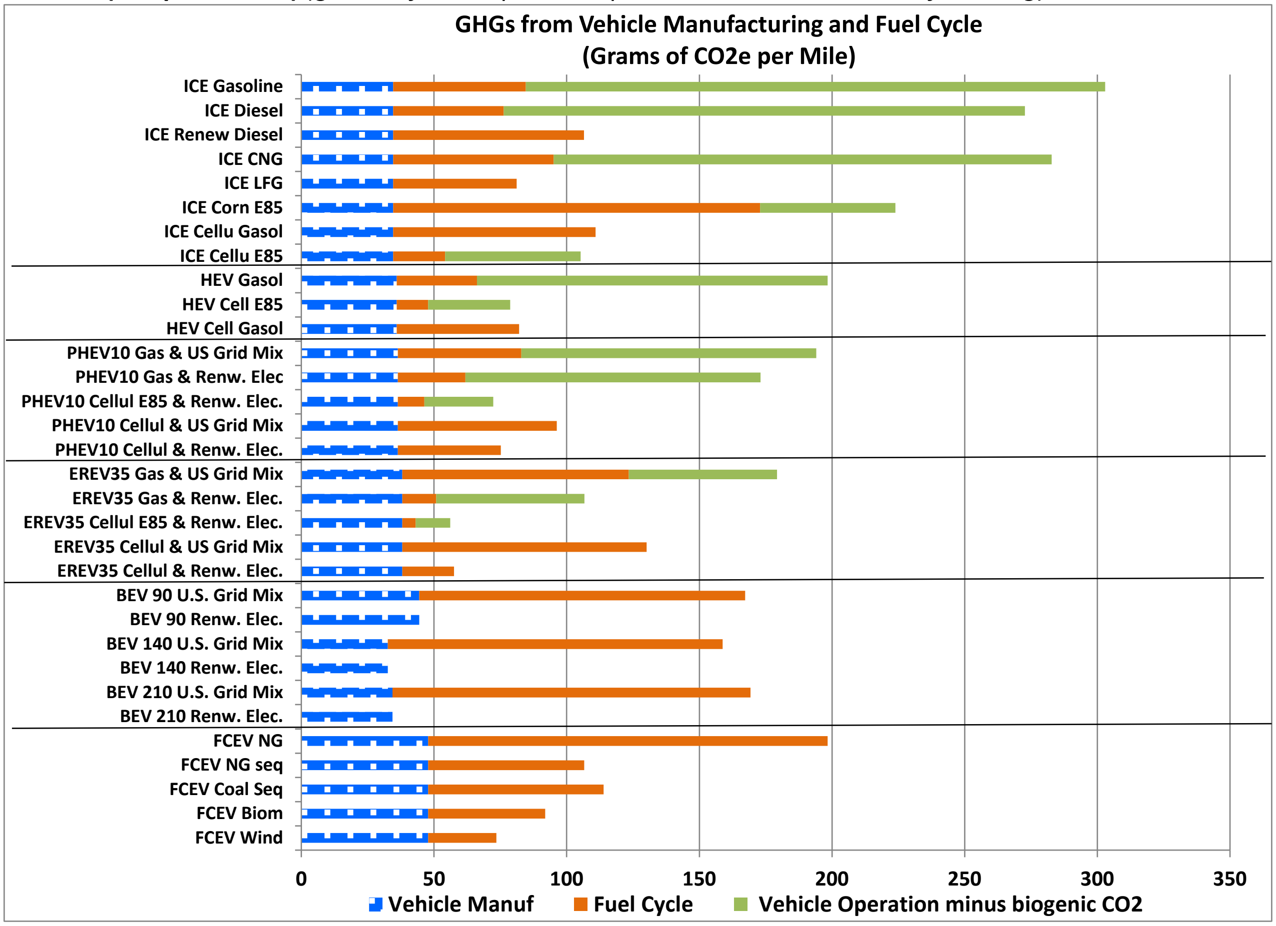
Figure 2. Life-Cycle Petroleum Use for 2035 Mid-Size Car *(Btus per mile, includes vehicle manufacturing)*



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

Figure 3 shows the breakout of GHG contribution of vehicle manufacturing versus the fuel cycle (including vehicle operation emissions) for the midpoint case.

Figure 3. Vehicle Cycle, Fuel Cycle, and Vehicle Operation: Greenhouse Gas Emissions for 2035 Mid-Size Car (Midpoint Case) *(grams of CO_2-equivalent per mile with vehicle manufacturing)*



Notes

1. *Carbon emissions from the use of biofuels exclude biogenic emissions, i.e., emissions associated with the combustion of organic matter, because this carbon is cycled by living organisms such as crops or grasses.*
2. *The carbon intensity of energy used in the vehicle cycle from the GREET model was not varied, resulting in point estimates (no high/low range) for BEVs on renewable electricity.*

Figure 4 shows the energy source breakout of total energy consumed for the midpoint case.

Data, Assumptions, References

Fuel economies for all fuel/vehicle systems were determined using ANL's Autonomie modeling simulation software that has been used to assess the fuel consumption and performance of advanced vehicle technologies. For information on Autonomie, see: http://www.anl.gov/energy-systems/project/tool-vehicle-system-simulation-autonomie.

The ANL GREET1 (2015 version) model was used to determine the well-to-wheels (WTW) GHG emissions and petroleum energy use associated with the extraction (or growth in the case of biofuels) of the primary feedstock, the transportation of the feedstock, the production of the fuel from the feedstock, as well as the transportation, distribution and use of the fuel during vehicle operation. The ANL GREET2 (2015 version) model for vehicle manufacturing cycle was used to calculate the energy use and GHG emissions associated with the production and processing of vehicle materials, the manufacturing and assembly of the vehicle, as well as the end of life decommissioning and recycling of vehicle components.[8] These models are available at https://greet.es.anl.gov.

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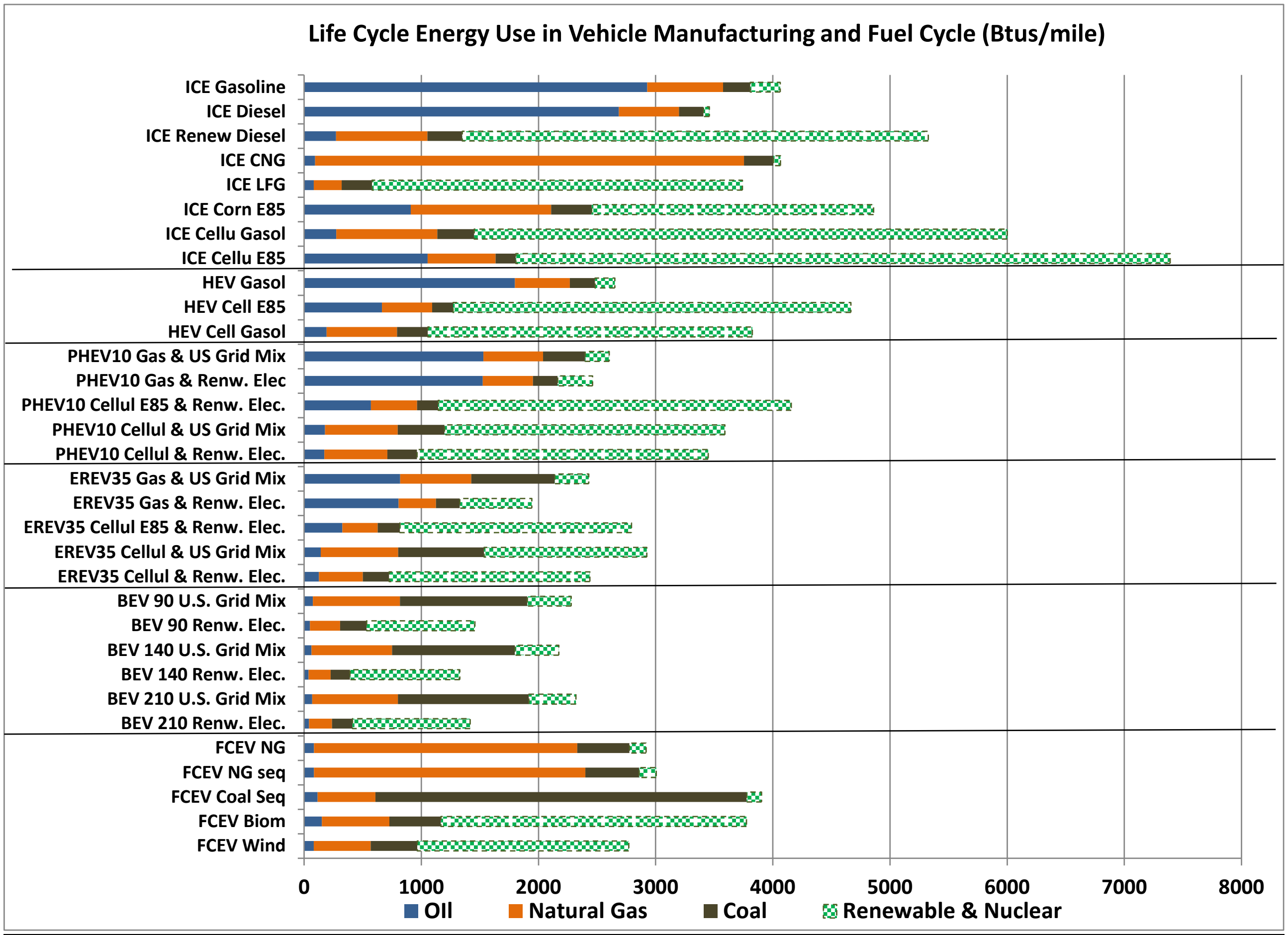
[8] As previously stated, assumed 178,000-mile vehicle lifetime, except for BEV90 (125,000 miles) (see annual vehicle miles survey results at http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf).

Fuel economy estimates for vehicles are based on the gallon gasoline energy equivalent (gge) of each applicable fuel, approximately 112,200 Btu per gallon of gasoline (lower heating value of reformulated gasoline containing nearly 10% ethanol by volume).

These results for GHG emissions and petroleum use will be periodically updated to reflect changes in the estimates and refinements in the previously mentioned models.

Figure 4. Life-Cycle Total Energy Use for 2035 Mid-Size Car (Midpoint Case) by Energy Source *(Btus per mile with vehicle manufacturing)*



Note: While GREET1 shows significant energy consumption for biomass pathways, this energy is not really comparable to conventional fuels because of its renewable nature.

Table 2 lists the GHG emissions and petroleum consumption per mile driven for the midpoint cases[9] for mid-size car. The right-hand column summarizes the fuel economy assumptions for the midpoint case along with possible ranges that bound the variability associated with achieving these estimates (only on-road fuel economy estimates 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 (from Autonomie vehicle simulations conducted late 2015–early 2016) and scenario-specific assumptions (such as the carbon intensity of electricity and the effect of excess electricity export to the grid for the cellulosic ethanol pathway) are illustrated in the charts.

[9] The Vehicle Technologies Office has three sets of potential R&D outcomes for LDV technologies: low, medium, and high technical progress.

Table 2. Assumptions and Detailed Results for 2035 Technologies (includes vehicle manufacturing)

Except for: (a) the variation in electricity's carbon intensity (CI) between California, the U.S. average grid, and Illinois; (b) the variation in cellulosic ethanol's CI due to assuming or not assuming the export of excess electricity from biomass to users outside of the biorefinery; and, (c) the variation in hydrogen's CI between assuming grid electricity versus low-carbon electricity for hydrogen transmission and delivery, each CI value shown below was assumed fixed for its representative technology, e.g., no sensitivity runs were made with respect to renewable diesel CI.

Vehicle/Fuel System Pathway	**Electricity Carbon Intensity, (CI_E, g CO_2e/kBtu)**	**Fuel Carbon Intensity (CI_F, g CO_2e/kBtu)**	**On-Road Fuel Economy**	**Life-Cycle GHG (g CO_2e/mile) & *Petroleum (BTUs/mile)***	**Notes**
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. Fuel economy ranges for these and the other LDVs analyzed were from the ANL Autonomie model.					
Today's Conventional Vehicle (E10)	n.a.	CI_F: 95	Current car: 27 mpgge	GHGs: 450/mile, *Petroleum: 4300/mile*	
Conventional: Gasoline (E10)	n.a.	95	40 mpgge (low/high: 35-46)	300/*2930*	
Conventional: Diesel	n.a.	96	45 (39-52)	270/*2690*	
Conventional: Renewable Diesel	n.a.	29	45 (39-52)	110/*270*	
Conventional: Corn Ethanol (E85)	n.a.	67	40 (35-46)	220/*910*	Indirect land use change assumed for corn crops in the main case shown in the bar chart. Fuel economy variability effects are illustrated with sensitivity bars.
Conventional: Cellulosic Ethanol (E85) [1]	n.a.	25	40 (35-46)	100/*1050*	Includes reductions in net GHG emissions and petroleum use that will occur through co-production and export of electricity.
Conventional: Cellulosic Gasoline	n.a.	27	40 (35-46)	110/*270*	
Conventional: CNG	n.a.	80	36 (32-42)	280/*94*	
Conventional Vehicle: CNG from landfill gas	n.a.	15	36 (32-42)	80/*82*	

Hybrid-Electric Vehicles:					
Sensitivity bars in the chart are based on the approach used for conventional LDVs.					
	CI_E, g CO_2e/kBtu	**CI_F, g CO_2e/kBtu**	**Fuel Economy, mpgge**	**g CO_2e/mi *Btu Petro/mi***	
Gasoline (E10)	n.a.	95	66 (55-79)	200/*1800*	
Cellulosic Ethanol (E85)	n.a.	25	same	79/*660*	Same assumptions as described in the bullets on this biofuel for the conventional LDVs.
Cellulosic Gasoline	n.a.	27	same	82/*190*	Same assumptions as described in the bullets on this biofuel for the conventional LDVs.

Plug-in Hybrid Electric Vehicle with 10-Mile Charge Depleting (CD) Range:

In this PHEV design, the gasoline engine will activate to assist the electric drive at higher loads such as during acceleration or on steep hills. Therefore the CD mode is actually a blended (electricity and gasoline) mode. The share of distance travelled in the blended mode was assumed to be 23% of the total distance driven by these PHEVs. A mid-size PHEV rated with 10-mile blended CD range was assumed to have an on-road (more realistic driving conditions) electricity consumption of 170 Wh/mile (146–197) in the blended mode of operation; and, (2) 66 mpgge (54–79) in the charge-sustaining (CS) mode. [3] Electricity consumption is from the battery, not the wall outlet, i.e., does not include battery and charging losses. For each of the 3 technical progress scenarios, the combined losses (electric vehicle supply system and battery) account for an additional 2%, 5%, and 8% reduction in efficiency (2035 technology progress assumptions by DOE). The effects of fuel economy variability are illustrated with the sensitivity bars.

PHEV10	**CI_E, g CO_2e/kBtu**	**CI_F, g CO_2e/kBtu**	**Fuel Economy, mpgge or Wh/mi**	**g CO_2e/mi** ***Btu Petro/mi***	
Gasoline (E10)	U.S. Grid: 150	95	CS 66 (54-79) mpgge, CD 201 (162-243) mpgge, 170 (197-146) Wh/mi	U.S. Grid: 190/*1530*	Besides fuel economy variability, the effect of regional variation in electricity's carbon intensity is illustrated using California and Illinois CI_E (CA: 76, IL: 226)
	Renewable Electricity: 0[10]	95	same	Renewable Electricity: 170/*1530*	
Cellulosic Ethanol (E85)	Renewable Electricity: 0	25	same	Renewable electricity: 72/*570*	
Cellulosic Gasoline	U.S.Grid: 150	27	same	U.S. Grid: 96/*180*	Same assumptions as described in the bullet on this biofuel for the conventional LDVs. Also, regional electricity variation is illustrated with CA and IL.
	Renewable Electricity: 0	27	same	Renewable Electricity: 75/*170*	

Extended-Range Electric Vehicle with 35-Mile Charge Depleting (CD) Range:

The share of distance travelled in the CD mode was assumed to be 58.5% of the total distance driven by these EREVs. The on-road CD range is approximately 35 miles for the EREV35. The engine (using liquid fuel) is not activated during the EREV's CD mode of operation. Electricity consumption simulated with Autonomie, is from the battery, not the wall outlet, i.e., does not include battery and charging losses. For each of the three technical progress scenarios, the combined losses (electric vehicle supply system and battery) account for an additional 2%, 5%, and 8% reduction in efficiency (2035 technology assumptions). The mid-size EREV with 35-mile CD range (city) was assumed to have an on-road electricity consumption of 230 Wh/mile (194-274) in CD; and, (2) 64 mpgge (47-81) in CS.

	CI_E, g CO_2e/kBtu	**CI_F, g CO_2e/kBtu**	**Fuel Economy, mpgge or Wh/mi**	**g CO_2e/mi** ***Btu Petro/mi***	
Gasoline (E10)	U.S. grid: 150	95	CS 64 (47-81) mpgge, CD 230 (194-275) Wh/mi	U.S. Grid: 180/*820*	Besides fuel economy variability, the effect of regional variation in electricity's carbon intensity is illustrated using California and Illinois CI_E (CA: 76, IL: 226)
	Renewable Electricity: 0	95	same	Renewable Electricity: 110/*810*	
Cellulosic Ethanol (E85)	Renewable Electricity: 0	35	same	Renewable Electricity: 56/*330*	Same assumptions as those described in the bullets on this biofuel for the conventional vehicles.

[10] GREET does not include GHGs from infrastructure construction, dismantling, and decommissioning.

Cellulosic Gasoline:	U.S. grid: 150		same	U.S. Grid: 130/*140*	Same assumptions as those described in the bullets on this biofuel for the conventional LDVs. Also, regional electricity variation is illustrated with CA and IL.
	Renewable Electricity: 0		same	Renewable Electricity: 58/*130*	

Battery Electric Vehicles:					
The on-road range is approximately 90 miles for the BEV90 and 210 miles for the BEV210 (source: previously cited Autonomie model). Electricity consumption does not include battery and charging losses. For each of the 3 technical progress scenarios, the combined losses (electric vehicle supply system and battery) account for an additional 2%, 5%, and 8% reduction in efficiency (2035 technology assumptions). The effects of fuel economy variability and electricity's carbon intensity are illustrated with the sensitivity bars in the figure.					
	CI_E, g CO_2e/kBtu	**CI_F, g CO_2e/kBtu**	**Fuel Economy, Wh/mi**	**g CO_2e/mi *Btu Petro/mi***	
Battery Electric Vehicle (90-mile electric range)	U.S. grid: 150	n.a.	228 (196-266)	U.S. Grid:170/*75*	Besides fuel economy variability, the effect of regional variation in electricity's carbon intensity is illustrated using California and Illinois CI_E (CA: 76, IL: 226)
	Renewable Electricity: 0	n.a.	same	Renewable Electricity: 44/*51*	
Battery Electric Vehicle (140-mile electric range)	U.S. grid: 150	n.a.	234 (201-274)	U.S. Grid: 160/64	Regional electricity variation as described for BEV90
	Renewable Electricity: 0	n.a.	same	Renewable Electricity: 33/*39*	
Battery Electric Vehicle (210-mile electric range)	U.S. grid: 150	n.a.	250 (214-295)	U.S. Grid: 170/*70*	Regional electricity variation as described for BEV90
	Renewable Electricity: 0	n.a.	same	Renewable Electricity: 34/*43*	

Fuel Cell Electric Vehicles:					
H_2 from central production plants is delivered by pipeline to the station in gaseous form at 300 psi. U.S. average grid electricity is assumed for pipeline delivery of H_2 and compression and dispensing at the fueling station. The effects of fuel economy variability are illustrated with sensitivity bars.					
	CI_E, g CO_2e/kBtu	**CI_F, g CO_2e/kBtu**	**Fuel Economy, mpgge**	**g CO_2e/mi *Btu Petro/mi***	
Refueling Station: Distributed Natural Gas	n.a.	123	92 (75-110)	200/*85*	Sensitivity includes the effects of fuel economy variability.
Central Plant: Natural Gas Reforming with Carbon Sequestration	n.a.	48	same	110/*85*	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 21).
Central Plant: Coal Gasification with Carbon Sequestration	n.a.	54	same	110/*120*	Sensitivity includes the parameters described above (CI of H_2 reduced to 33).
Central Plant: Biomass Gasification	n.a.	36	same	92/*150*	Feedstock is a short-rotation woody crop (hybrid poplar). Sensitivity includes the parameters described above (CI of H2 reduced to 11).

Central Plant: Wind for H_2 production and grid electricity for delivery, storage, and dispensing	n.a.	21	same	74/*83*	Sensitivity includes the parameters described above (CI of H_2 reduced to virtually 0).