DOE Hydrogen and Fuel Cells Program Record	
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Title: Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways	
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Approved by: Sunita Satyapal	**Date: March 24, 2014**
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1. Introduction

The desire for improved energy security and reduced CO_2 emissions has led to a substantial research effort to provide road transportation options that reduce the use of petroleum-based fuels and the release of greenhouse gases and air pollutants into the atmosphere. Advanced vehicle technologies include lighter, more efficient gliders (chassis, body, etc.) and powertrain improvements for more efficient internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). Fuel technologies under consideration include petroleum fuels (gasoline and diesel), biofuels, compressed natural gas, electricity for plug-in vehicles, and hydrogen (H_2) for FCEVs. To inform policy and guide product development plans, the environmental merits of these various technologies must be understood. This requires a holistic perspective that can be achieved via life-cycle analysis.

Life-cycle analyses (LCAs) of energy use and greenhouse gas (GHG) emissions for light-duty vehicles in previous DOE Records have focused on the transportation fuel cycle, also known as well-to-wheels (WTW) [1]. Such LCAs consist of well-to-pump (WTP) and pump-to-wheels (PTW) portions. The WTW analysis does not traditionally include vehicle cycle energy use and emissions – those associated with the vehicle manufacture. The justification for excluding the vehicle cycle in previous works stems from the understanding that GHG emissions associated with the vehicle cycle are an order of magnitude less than fuel cycle GHG emissions for conventional gasoline ICEVs [2–6]. However, for advanced vehicle technologies that utilize alternative fuels, e.g., BEVs and FCEVs, the fuel cycle (or WTW) energy use and GHG emissions decrease while the vehicle cycle energy use and GHG emissions increase. Hence, both vehicle and fuel cycles must be considered in a cradle-to-grave (C2G) analysis when evaluating advanced fuel-vehicle systems. A C2G analysis encompasses resource extraction (cradle), transformation of resources into fuels and vehicles, vehicle operation, and vehicle end-of-life disposal and recycling[1] (grave).

A C2G project for evaluating the energy and emission impacts of various fuel-vehicle systems was initiated and sponsored by DOE's EERE Fuel Cell Technologies (FCT) and Vehicle Technologies (VT) Offices with participation from the energy and automobile industries. Argonne National Laboratory carried out the C2G analysis for two bookend scenarios: (1) current fuel production pathways and vehicle technology options, and (2) fuels and vehicles in a hypothetical 100% biomass based fuel and zero carbon electricity world[2]. The analysis was carried out by expanding and modifying the GREET^{TM} (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) model[3] suite [7] with inputs from industrial experts. Figure 1 shows the main life cycle stages covered by the fuel cycle model (GREET1) and the vehicle cycle model (GREET2). The GREET1 model calculates the energy use and emissions 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 GREET2 model calculates the energy use and 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.

Argonne evaluated the life-cycle energy use and GHG emissions of two bookend scenarios ("Current" and "Hypothetical low carbon") of various fuel production pathways and vehicle technologies. The "Current" bookend evaluates current fuel production and vehicle technologies using current feedstock sources and process fuel mixes. The "Hypothetical low carbon" bookend evaluates potential future low-carbon production pathways for fuels, including 100% biomass derived gasoline, diesel, natural gas, cellulosic ethanol and zero carbon based electricity, and future vehicle technologies that meet certain energy/emissions performance

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[1] The recycling impact is manifested in the material composition of each component. GREET evaluates the impact of virgin vs. recycled materials separately and combines them, when applicable, at the vehicle component level.

[2] This scenario is not a reflection of what we believe could be achievable in the timeframe selected for this analysis (2030), but rather to establish an extreme case to set the boundary against which intermediate scenarios could be assessed.

[3] GREET1 2012 rev2 and GREET2 2012 rev1 were used for this C2G analysis

targets. The hypothetical low carbon pathways do not account for cost, supply, or technical barriers which would prevent or delay the introduction of these options. The "Current" and "Hypothetical low carbon" bookends represent high and low estimates of GHG emissions, respectively, for each evaluated fuel-vehicle system. The "bookends" approach was chosen for this C2G analysis because it covers a sufficient range of energy use and GHG emissions of given vehicle/fuel technologies to uncover any sensitivities to this range in the overarching conclusions of the analysis. Planned future work will identify realistic scenarios that fall between the bookends. The cost of implementing scenarios is an important consideration for the evaluation of the feasibility and sustainability of any current or future options. However, evaluating the cost of various fuels and vehicle technologies for the current and hypothetical low carbon cases is outside the scope of this study.

The "Hypothetical low carbon" case premises 100% biomass derived fuels and zero carbon electricity and assumes that the fuels production technology, infrastructure, and supply of biomass are available to fill the market demand for 2030[4]. The logistics and economics impacts of the 2030 case are also outside the scope of this study.

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[4] The year 2030 was selected for the hypothetical low-carbon case because we expect that regulations and market conditions will drive much greater availability of renewable fuels and vehicle technologies with higher efficiencies.

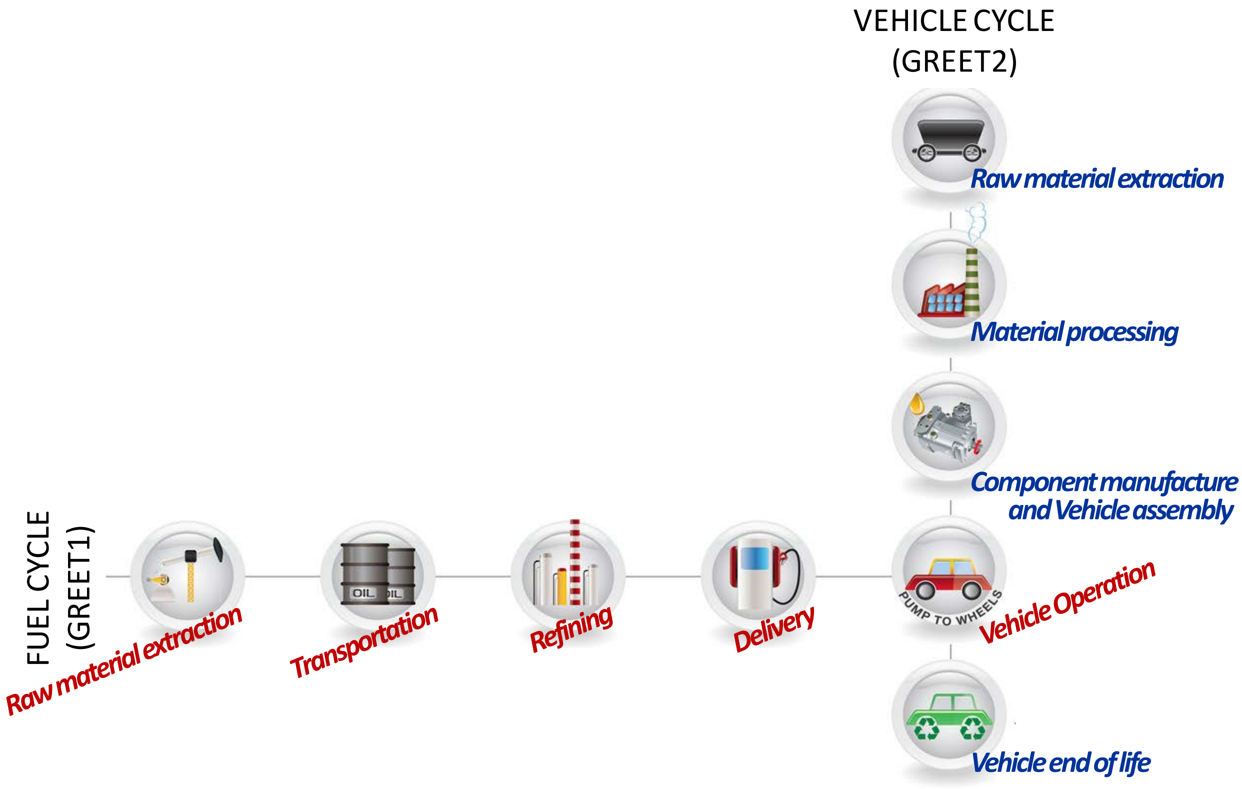

Figure 1. Combined fuel cycle and vehicle cycle activities included in C2G analysis

2. Fuel - Vehicle Pathways

A broad spectrum of vehicle-engine types and fuel options were analyzed. The primary intent was to gain an understanding of energy use and greenhouse gas emission ranges for each fuel-vehicle combination and compare across various combinations. Table 1 shows the fuel-vehicle combinations that were analyzed. Each X (or fractional miles X%) within the table designates a vehicle-fuel combination for which the two bookends were analyzed.

Table 1. Fuel-vehicle combinations analyzed

	Gasoline[ï]	**Diesel**	**CNG**	**E85**[Ŧ]	**H_2**	**Electricity**
ICEV	X	X	X	X		
HEV	X					
FCEV					X	
BEV70[*]						X
BEV210[+]						X
PHEV10[¥]	75%[§]					25%[§]
PHEV28[‡]	50%[§]					50%[§]

[ï] Gasoline has 10% corn ethanol by volume.
[Ŧ] Blend of 85% ethanol fuel grade with gasoline by volume for modeling purposes (commercial E85 can contain 51-83v% ethanol for seasonality and RVP limits)
[*] BEV70 has 70 miles "on-road" driving range.
[+] BEV210 has 210 miles "on-road" driving range.
[¥] PHEV10 has 10 miles "on-road" electric range and is modeled as a power-split PHEV.
[‡] PHEV28 has 28 miles "on-road" electric range is modeled as an Extended Range Electric vehicle (EREV).
[§] The fraction of total miles driven on fuel or electricity per SAE J2841 - Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data.

The vehicle class chosen for this analysis was the mid-size[5]. Vehicle fuel economies and component sizes were estimated by ANL's vehicle simulation tool, *Autonomie* [8], using a consistent set of vehicle performance criteria across fuel-vehicle combinations. Each vehicle is presumed to be optimized for the fuel on which it operates. Inputs to *Autonomie* were based on vehicle manufacturers' information and ANL assumptions [9]. Vehicles modeled in *Autonomie* met the following criteria:

- Vehicle acceleration from 0 to 60 mph in 9 sec (+/- 0.1 sec)
- Gradeability of 6% at 65 mph at Gross Vehicle Weight (GVW)
- Maximum vehicle speed >= 100 mph
- 160,000 lifetime miles per vehicle – except for BEV70 at 110,000 miles due to limited range

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[5] Typically with five seating capacity and passenger plus cargo space of 110-120 ft^3

For the two bookends shown in Table 2, upper bounds in terms of GHG emissions are based on technology options available now and today's average fuel mixes. The current energy mix and efficiencies were extracted from the 2010 data of the Energy Information Administration's (EIA's) Annual Energy Outlook 2011 (AEO11) and Canadian Association of Petroleum Producers (CAPP 2011) [10, 11]. Vehicle fuel economy was calculated using *Autonomie*. This upper bound is labeled as "Current" in the C2G energy use and GHG emissions charts.

The hypothetical low carbon bookend is based on hypothetical assumptions of fuel pathways with low GHG emissions. Although growth in availability and volume of low-carbon fuels is expected due in part to government mandates, the low-carbon or zero-carbon fuels required for this scenario (100% bio-derived gasoline and diesel, renewable natural gas and hydrogen, cellulosic ethanol, and zero-carbon power) are not expected to have significant market share by year 2030. They are included in this analysis only to represent a lower emissions limit, not necessarily a practically or economically viable scenario. However, for this hypothetical low carbon case, energy demand for all processes upstream or downstream of the fuel production (e.g., the heat and electricity for steel production, the electricity to compress natural gas or hydrogen) are based on the current AEO11 reference case projections for energy and fuel mixes in 2030. Fuel economy improvement estimates are based on potential adoptions of vehicle and powertrain technologies in the 2025/2030 timeframe. This bookend is labeled as "Hypothetical low carbon" in the C2G energy use and GHG emissions charts.

An intermediate case showing the effects of vehicular fuel economy improvements (with no changes to the energy mix or efficiencies of fuel production) is also reported so that the contributions of fuel economy improvements can be partially decoupled from the contributions of the energy mix. The results for this case were generated using today's energy source data (as used in the "Current" case) and the fuel economies projected in the 2025/2030 timeframe (as used in the "Hypothetical low carbon" case). This result is labeled as "Vehicle Efficiency Gain" in the C2G energy use and GHG emissions charts.

Table 2. Definitions of fuel production pathways for each bookend

	Current	**Hypothetical Low Carbon***
Gasoline	average crude mix supplied to U.S. refineries	Drop-in bio-based gasoline from corn stover (via pyrolysis)
Diesel	average crude mix supplied to U.S. refineries	Drop-in bio-based diesel fuel from corn stover (via pyrolysis)
CNG	average U.S. conventional and shale gas supply mix	Renewable natural gas (e.g., from landfill gas)
Ethanol	average corn dry-mill and wet mill plants	Cellulosic ethanol from corn stover
Hydrogen	Central production from steam methane reforming (SMR)	Water electrolysis via zero-carbon power**
Electricity	U.S. average electricity generation mix	Zero-carbon power**

*100% biomass derived gasoline, diesel, natural gas, cellulosic ethanol and zero carbon based electricity for hydrogen and plug-in vehicles.

** Zero-carbon power is generated from wind, solar, and hydro sources.

3. Key Assumptions for Fuel Production Pathways

The key parametric assumptions and their technical variability for the "Current" scenario of individual fuel production pathways are summarized in Table A1 in the appendix, while appendix Table A2 summarizes the key assumptions for the "Hypothetical low carbon" scenario of individual fuel production pathways in 2030. Land use change, (LUC), and other indirect effects of biofuel-related agriculture carry with them high uncertainties. For this analysis, the Global Trade Analysis Project (GTAP) model was used to calculate LUC used in the GREET model for corn ethanol [12]. Other models and calculations for LUC exist. These models were constructed using different assumptions and datasets. They give a wide range of LUC emissions results for the same biofuel pathway, many of which fall outside those used in this paper. Figure 2a shows estimates for LUC contributions to corn ethanol GHG emissions using different models and assumptions. Figure 2b shows a range of GHG emissions attributed to corn ethanol when adding LUC GHG emissions from different studies [12, 13, 14–21] to the C2G GHG emissions estimated by this study for the case without LUC. A recent CRC workshop concluded that "considerable improvements appear to be happening in the area of LUC assessment" [22]. LUC estimates in the literature are generally lower than the original Searchinger estimates (see Figure 2a), but significant variation remains. A detailed discussion of LUC uncertainty and the variability associated with the hypothetical low carbon case is outside the scope of the present study.

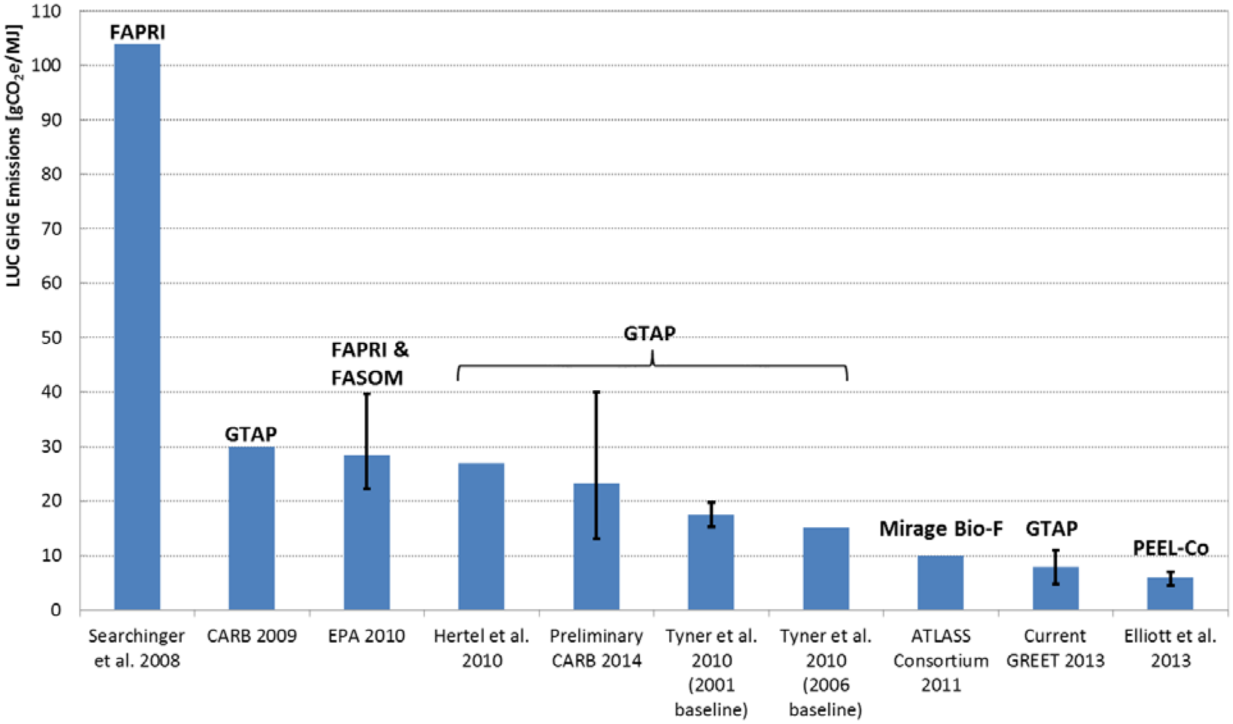

Figure 2a. Estimates for LUC contribution to GHG emissions for corn ethanol

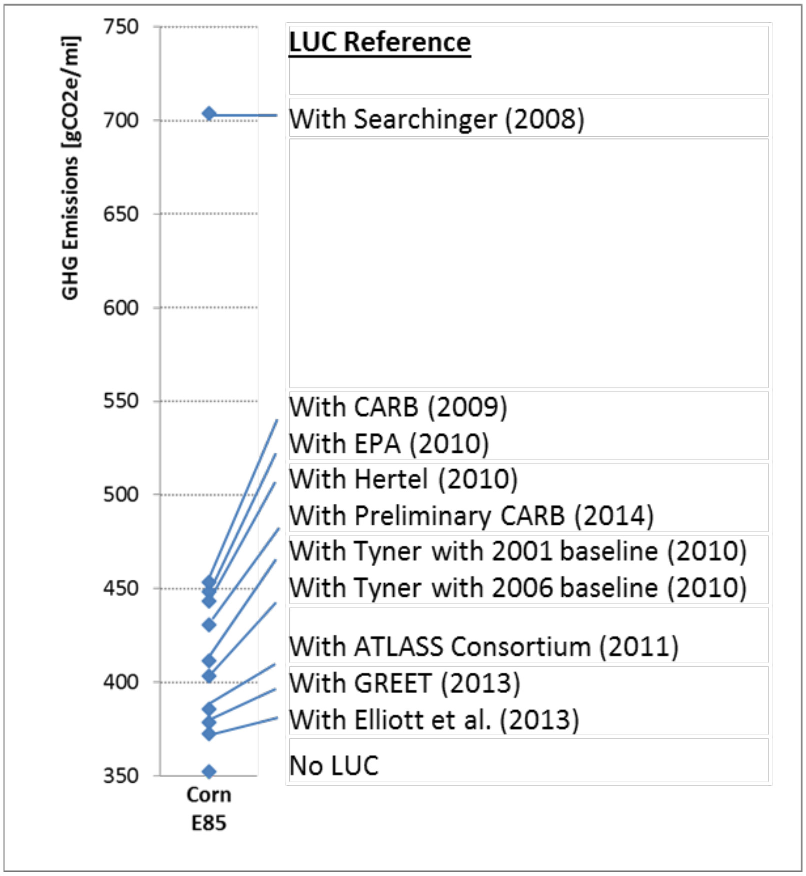

Figure 2b. Range of GHG emissions attributed to corn ethanol when adding LUC GHG emissions from different studies to the C2G GHG emissions estimated in the present study for the case without LUC.

4. Key Assumptions for Vehicle Technologies

The key parametric assumptions for various vehicle technologies for the "Current" scenario as represented by vehicle model year 2010, and "Hypothetical low carbon" scenario as represented by vehicle model year 2025[6] are summarized in the appendix (Table A3). For the set of vehicles examined, fuel economies are expressed as a percentage improvement relative to a conventional baseline gasoline ICEV in miles per gasoline-gallon equivalent (MPGGE). Fuel economy assumptions for advanced vehicle technologies are the result of a discussion with vehicle manufacturers, Argonne National Laboratory and DOE's Vehicle Technologies Office. Since EPA's urban and highway drive cycles do not account for more aggressive and higher speed driving, or the use of accessories (e.g., air conditioning), the fuel economy from the test cycles was adjusted to estimate "on-road" real world fuel economy using EPA formulas and methodology [23, 24] as explained in Elgowainy et al. [25].

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[6] It is assumed that for each vehicle class, model year 2025 provides good representation of that class in 2030

5. C2G Results

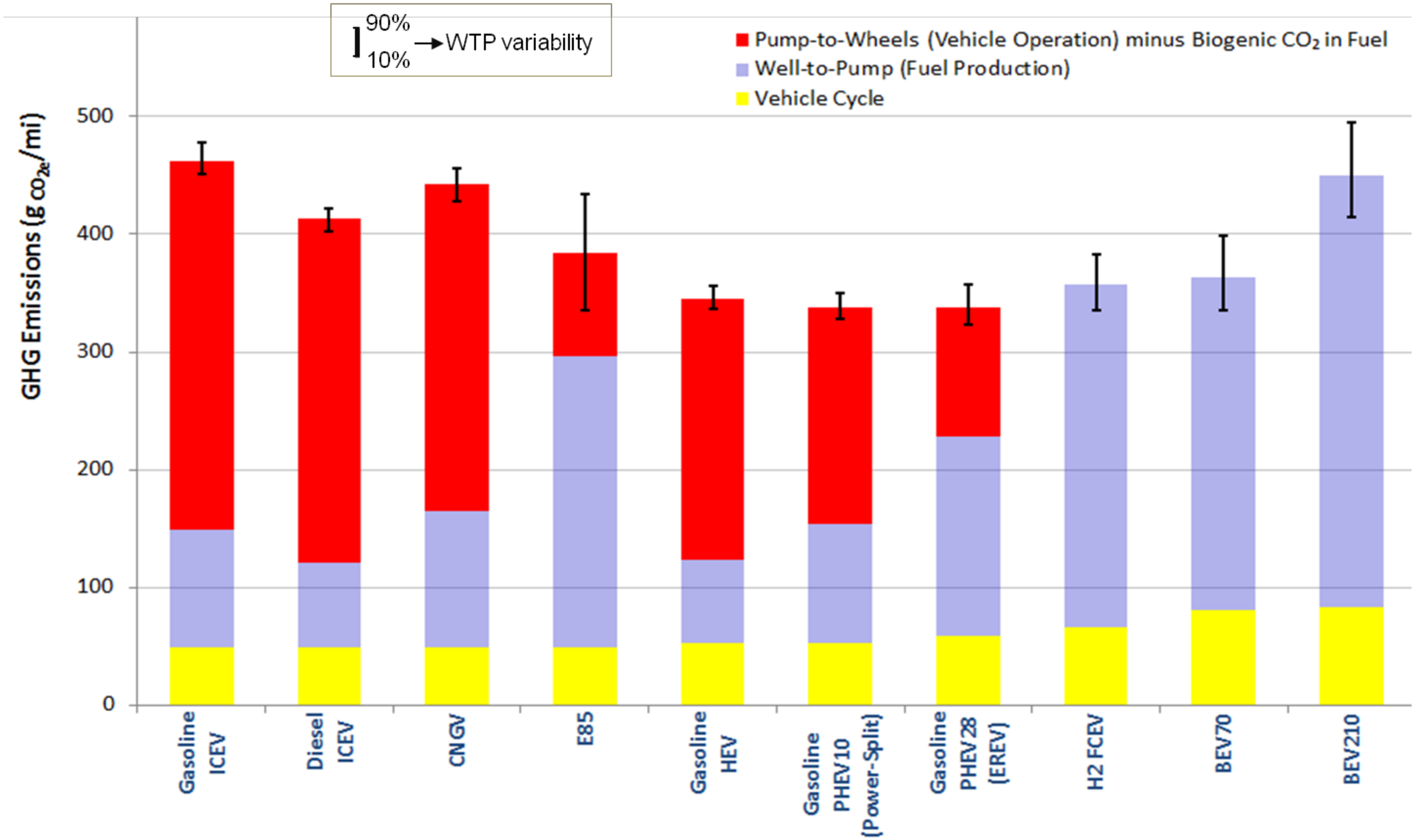

Figure 3. C2G GHG emissions for "Current" bookend showing contribution for vehicle cycle, fuel production and vehicle operations (fuel combustion).

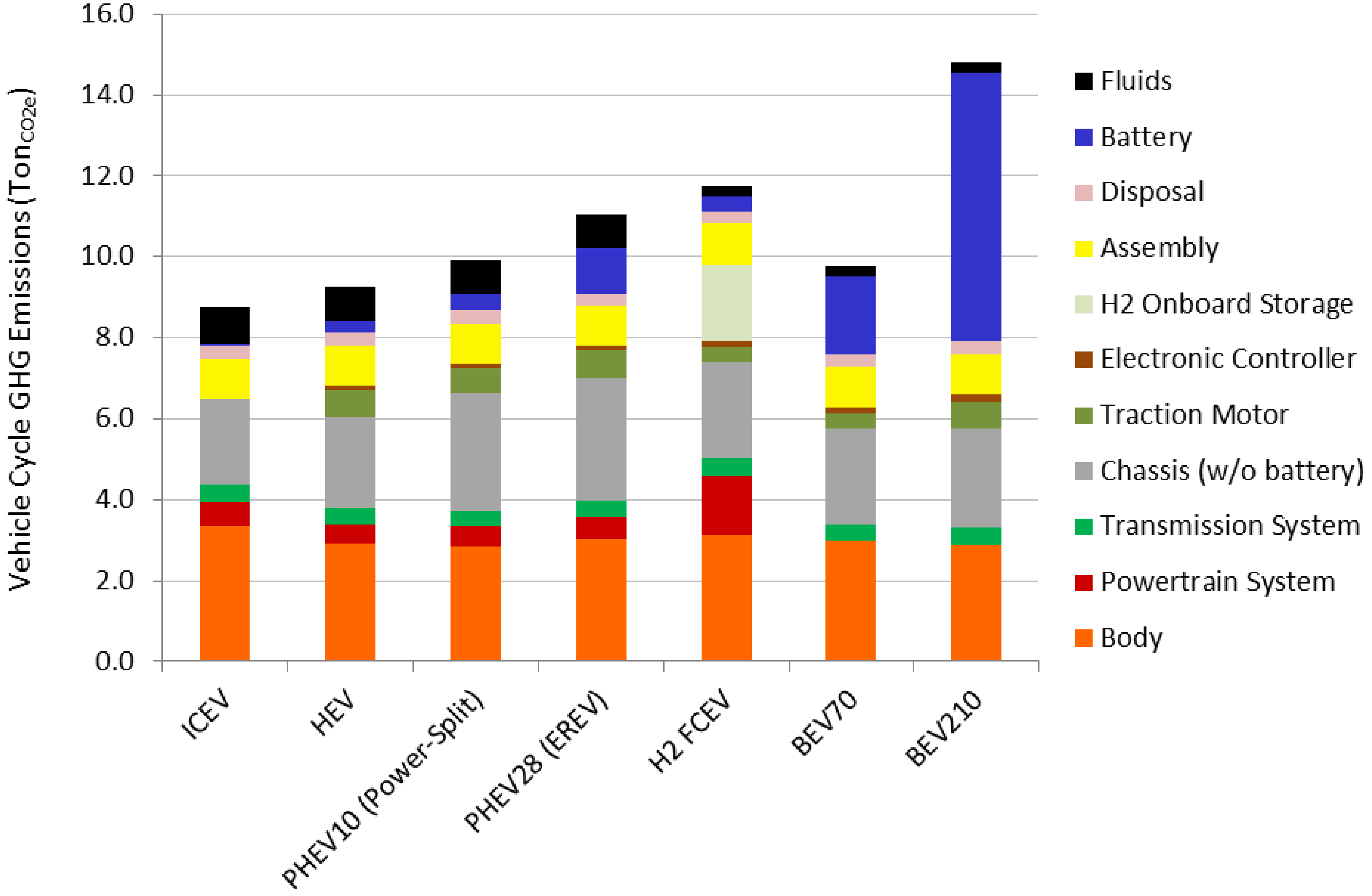

Figure 4. Vehicle cycle GHG emissions by vehicle components for ("Current") bookend represented in tons of CO_{2e}.

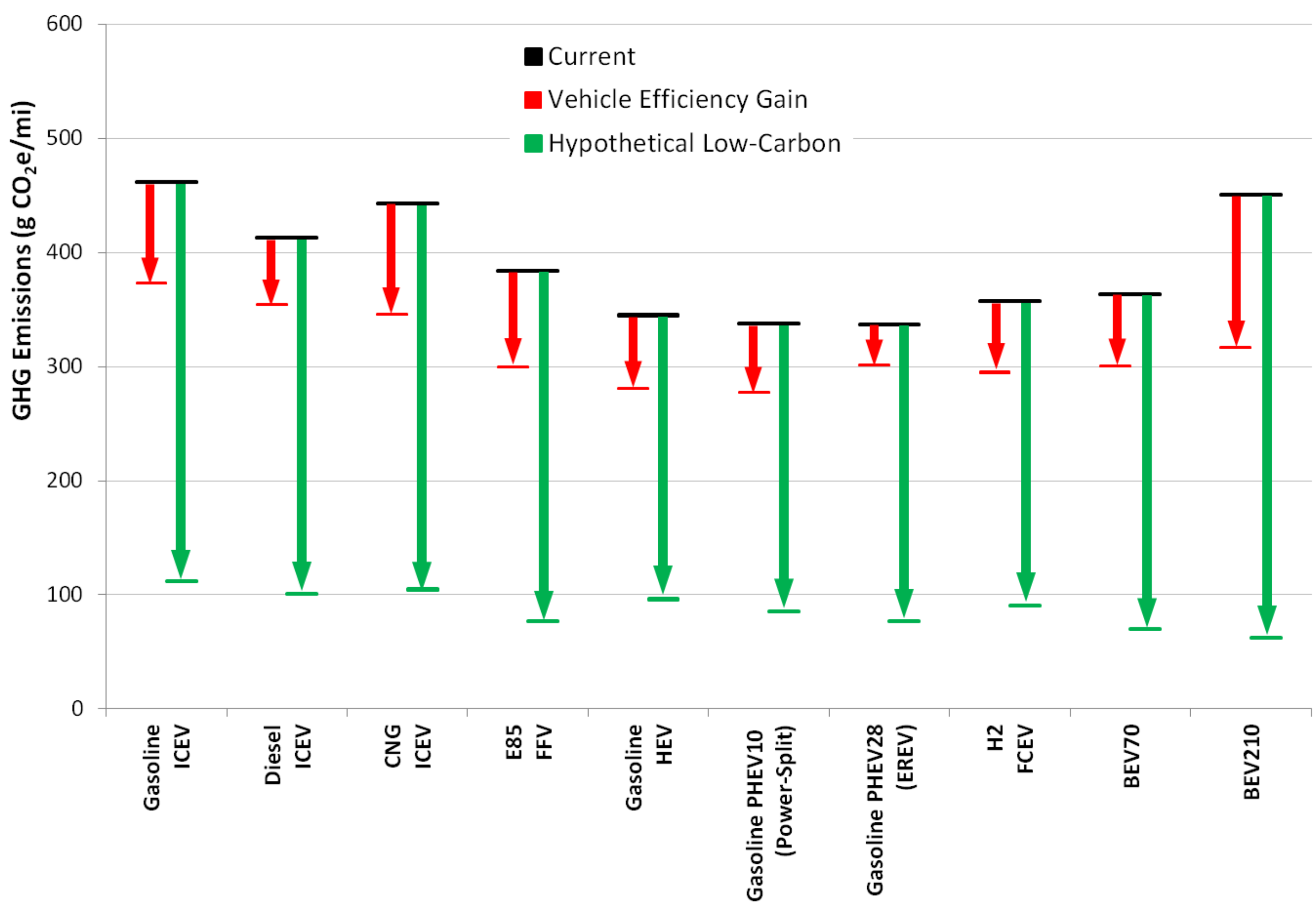

Figure 5. C2G GHG emissions for two bookends (“Current” and “Hypothetical low carbon”*) and the intermediate case (“Vehicle Efficiency Gains”). Contributions of vehicle cycle, fuel production and vehicle operations are shown in the appendix.

*100% biomass derived gasoline, diesel, natural gas, cellulosic ethanol and zero carbon based electricity for hydrogen and plug-in vehicles

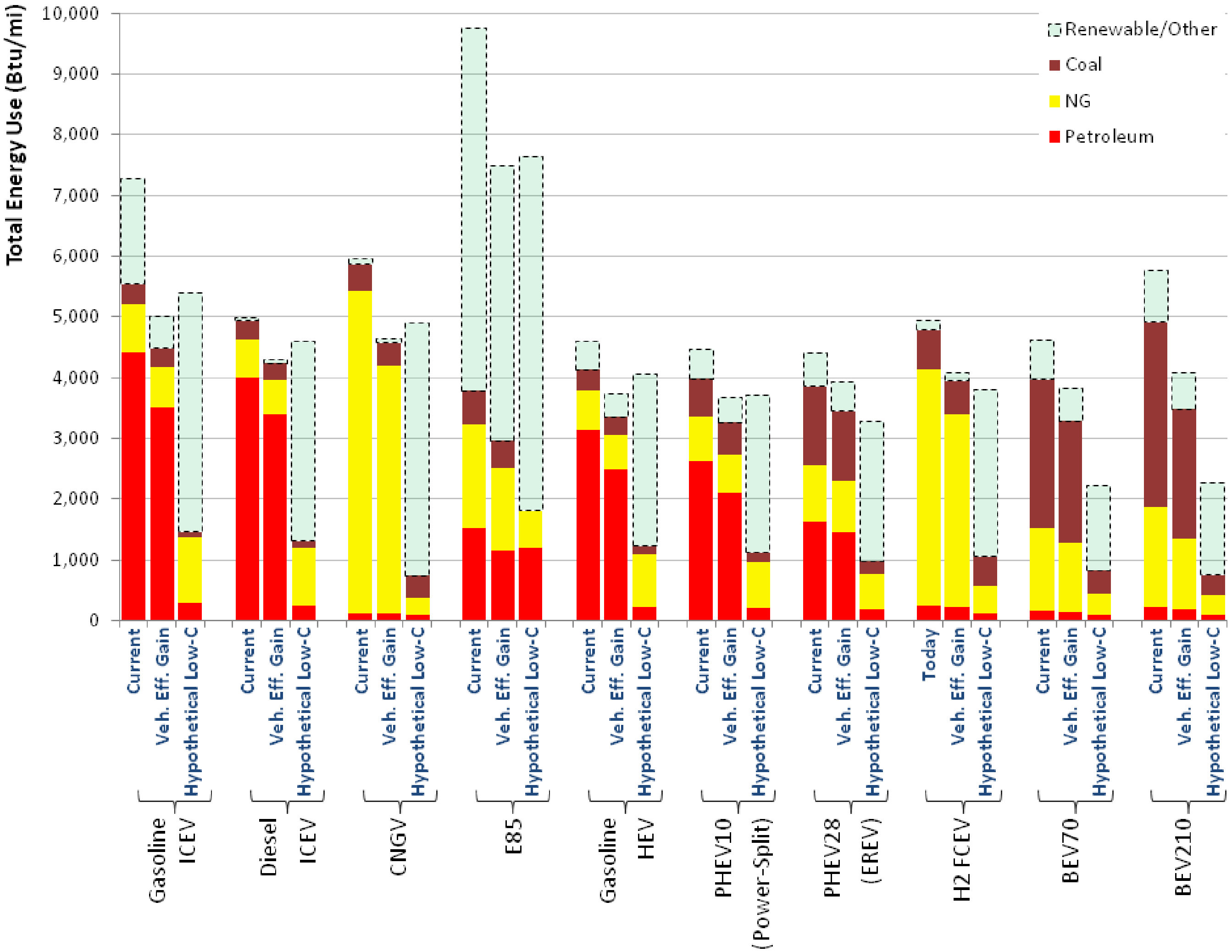

Figure 6. C2G total energy use for two bookends ("Current" and "Hypothetical low carbon"*) and the intermediate case ("Vehicle Efficiency Gains") represented in BTU per mile for four energy sources: petroleum, natural gas, coal, renewable/other.

*100% biomass derived gasoline, diesel, natural gas, cellulosic ethanol and zero carbon based electricity for hydrogen and plug-in vehicles

6. Conclusions

A Cradle-to-Grave analysis was conducted for GHG emissions and energy use of U.S light-duty fuel-vehicle technology combinations. Both vehicle efficiency gains and low-carbon energy sources can achieve large reductions in GHG emissions. Including the vehicle cycle with the fuel cycle did not change the relative GHG emission impacts of various pathways seen in previous DOE WTW records [1]. The contribution of the vehicle cycle is 10-22% of today's ("Current" scenario) C2G GHG emissions. For today's plug-in vehicles, the battery cycle contribution to C2G GHG emissions is 1-8%.

7. Acknowledgements

The C2G analysis of various fuel-vehicle pathways underwent a review process by industrial stakeholders, energy companies, automobile companies, electric generation organizations, and national laboratories.

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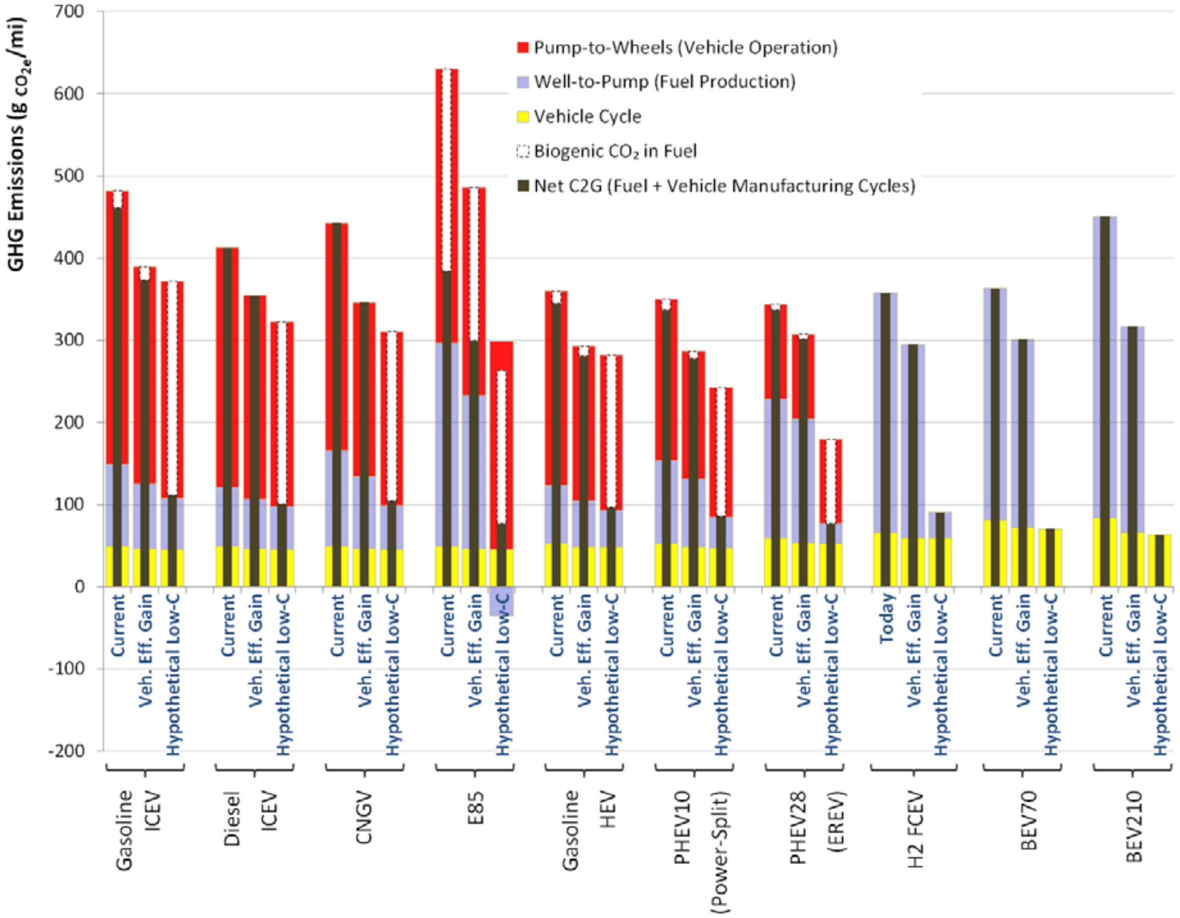
9. Appendix



Contributions of vehicle cycle, fuel production and vehicle operations to C2G GHG emissions.

Table A1. Key assumptions for processes in fuel production pathways of the "Current" bookend (2010 timeframe)

Pathway	Key Parameters	Assumption (and distribution type and definition when applicable)	Data Sources and Comments
Petroleum (Gasoline and Diesel)	Conventional crude - recovery efficiency (oil sands assumptions can be found in GREET [7])	98%, Triangular (Mean: 98%, p10: 97.4%, p90: 98.6%)	Brinkman et al. [26]
	Conventional crude - CH_4 from associated gas flaring/venting: grams/mmBtu of crude	80.3, Gamma (Scale: 160.3, Shape: 0.46, Location: 6.335)	Distribution generated by maximization of goodness-of-fit to the data compiled in Palou-Rivera et al. [27]
	Conventional crude - CO_2 from associated gas flaring/venting: grams/mmBtu of crude	1,430, Gamma (Scale: 2,289, Shape: 0.608, Location: 6.556)	Distribution generated by maximization of goodness-of-fit to the data compiled in Palou-Rivera et al. [27]. Additional references: EPA [28, 29] and World Bank [30]
	Refining efficiency for gasoline and diesel	90.6%, Normal (Mean: 90.6%, SD: 1.3%)	The type and shape of distribution functions were developed in Brinkman et al. (2005). The means of the distributions were scaled to the values in Palou-Rivera et al. [27]. Additional reference: Bredeson et al. [31]
	Lower heating values of crude oil (Btu/gal)	129,670, Triangular (Min: 129,000, Likeliest: 129,670, Max: 130,000)	Brinkman et al. [26]
	Lower heating values of conventional gasoline (Btu/gal)	116,090, Triangular (Min: 108,000, Likeliest: 116,090, Max: 123,500)	Brinkman et al. [26]
	Lower heating values of low sulfur diesel (Btu/gal)	129,490, Triangular (Min: 121,030, Likeliest: 129,490, Max: 141,740)	Brinkman et al. [26]

North American natural gas	Share of shale gas in total natural gas supply in the U.S.	22.6%	EIA AEO 2011 [11]
	North American conventional natural gas recovery efficiency	95.7%, Normal (Mean: 95.7%, SD: 1.8%)	Burnham et al. [32]
	North American shale gas recovery efficiency	96.5%, Normal (Mean: 96.5%, SD: 1.8%)	Burnham et al. [32]
	North American conventional and shale gas processing efficiency	97.2%, Normal (Mean: 97.2%, SD: 1.8%)	Burnham et al. [32]
	CO_2 venting, methane leakage, flaring per mmBtu of recovered gas		
	- Conventional and shale natural gas flared	7,585 g/mmBtu	Burnham et al. [32]. Additional references: EPA [28, 29]
	- CO_2 venting from conventional and shale gas recovery	41.4 g/mmBtu	Burnham et al. [32]. Additional references: EPA [28, 29]
	- CH4 Leakage from conventional gas recovery	398.7 g/mmBtu	Burnham et al. [32]. Additional references: EPA [28, 29]
	- CH4 Leakage from shale gas recovery	245.5 g/mmBtu	Burnham et al. [32]. Additional references: EPA [28, 29]
	Loss rate in natural gas pipelines	0.83%	Burnham et al. [32]
	NG compression efficiency at refueling station: NG engine	93.1%, Normal (Mean: 93.1%, SD: 1.2%)	Brinkman et al. [26]
	NG compression efficiency at refueling station: electric compressor	97.3%, Triangular (Min: 96.3%, Likeliest: 97.3%, Max: 98.3%)	Brinkman et al. [26]
	Lower heating value of NG	Triangular (Min: 961, Likeliest: 983, Max: 997)	Brinkman et al. [26]

Corn Ethanol	Farming energy (Btu/bushel of corn)	9,608, Weibull (Shape: 1.05, Scale: 2,000, Location: 7,648)	The type and shape of distribution functions were developed in Brinkman et al [26]. The means of the distributions were scaled to the values in Wang et al. [33].
	Nitrogen fertilizer input (grams/bushel of corn)	415, Normal (Mean: 415, SD: 77.7)	The type and shape of distribution functions were developed in Brinkman et al [26]. The means of the distributions were scaled to the values in Wang et al. [33]
	Fraction N fertilizer converted to N in N_2O	1.525%, Weibull (Shape: 0.91, Scale: 0.01, Location: 0.003)	Wang et al. [12]
	Share of dry mill vs. wet mill (%)	89% vs. 11%	Wang et al. [33]
	Dry mill		
	- Ethanol plant energy use (Btu/gallon of ethanol)	26,860, Normal (Mean: 26,860, SD: 5,410)	The type and shape of distribution functions were developed in Brinkman et al (2005). The means of the distributions were scaled to the values in Wang et al. [33]
	- Ethanol yield (gallons/bushel of corn)	2.8, Triangular (Min: 2.64, Likeliest: 2.8, Max: 2.96)	The type and shape of distribution functions were developed in Brinkman et al (2005). The means of the distributions were scaled to the values in Wang et al. [33]
	Wet mill		
	- Ethanol plant energy use (Btu/gallon of ethanol)	47,410, Normal (Mean: 47,410, SD: 7,070)	The type and shape of distribution functions were developed in Brinkman et al (2005). The means of the distributions were scaled to the values in Wang et al. [33]
	- Ethanol yield (gallons/bushel of corn)	2.61, Triangular (Min: 2.46, Likeliest: 2.61, Max: 2.76)	The type and shape of distribution functions were developed in Brinkman et al (2005). The means of the distributions were scaled to the values in Wang et al. [33]
	CO_2 from land use change (LUC) associated with the production of 15 billion gallons of corn ethanol:		
	- Domestic	447 (g CO_2/gallon of ethanol)	Mueller et al. [34], Tyner et al. [13]
	- Foreign	285 (g CO_2/gallon of ethanol)	Mueller et al. [34], Tyner et al. [13]

US Electricity Generation Mix	Electricity generation mix in 2011	0.6% residual oil, 25% natural gas, 42.7% coal, 19.3% nuclear, 1.1% biomass, 11.4% renewables	EIA, AEO [11]
	Grid transmission loss	6.5%	Cai et al. [35] based on eGrid 2010 [36]
	Generation technology efficiency		
	- Residual oil boiler	32.8%, Weibull (Shape: 17.4, Scale: 33.9%, Location: 0%)	Cai et al. [35] based on eGrid 2010 [36]
	- NG boiler	31.9%, Logistics (Mean: 31.9%, Scale: 2.4%)	Cai et al. [35] based on eGrid 2010 [36]
	- NG gas turbine	32.6%, Normal (Mean: 32.6%, SD: 5.1%)	Cai et al. [35] based on eGrid 2010 [36]
	- NG combined cycle	49.8%, Weibull (Shape: 54.5, Scale: 161%, Location: -109%)	Cai et al. [35] based on eGrid 2010 [36]
	- Coal boiler	34.5%, Logistics (Mean: 34.5%, Scale: 1.7%)	Cai et al. [35] based on eGrid 2010 [36]
	- Biomass boiler	20.8%, Logistics (Mean: 20.8%, Scale: 2.4%)	Cai et al. [35] based on eGrid 2010 [36]
	Carbon content of coal	58.6%	Cai et al. [35] based on USGA database [37]
	Lower heating values of coal	19,474,000 Btu/ton	Cai et al. [35] based on USGA database [37]
Hydrogen production from SMR of natural gas	Central plant H_2 production efficiencies	71.5%, Normal (Mean: 71.5%, SD: 4.16%)	Brinkman et al. [26]
	Gaseous H_2 compression efficiency	91.5%, Triangular (Min: 90.8%, Likeliest: 91.5%, Max: 93.3%)	Hydrogen Delivery Scenario Analysis Model (HDSAM), version 2.3 [38]

Table A2. Key assumptions for fuel production pathways of the "Hypothetical low carbon" bookend (2030 timeframe)

Pathway	**Key Parameters**	**Assumption**	**Data Sources and Comments**
Pyrolysis-based gasoline and diesel	a) Corn Stover Collection		
	Corn Stover Collection Energy	192,700 Btu/dry ton	Han et al. [39]
	Supplemental Fertilizer Use: N	7,700 g/dry ton	Han et al. [39]
	Supplemental Fertilizer Use: P2O5	2,000 g/dry ton	Han et al. [39]
	Supplemental Fertilizer Use: K2O	12,000 g/dry ton	Han et al. [39]
	b) Pyrolysis & Stabilization of pyrolysis oil		
	Biomass Use	2.82 lb biomass/lb pyrolysis oil	Wright et al. [40]. Additional Reference: Jones et al [41]
	Electricity Use	656 Btu/lb pyrolysis oil	Wright et al. [40]
	NG Use	3,390 Btu/lb pyrolysis oil	Wright et al. [40]
	Co-products: Char (credit)	3,853 Btu/lb pyrolysis oil	Wright et al. [40]
	c) Liquid fuel Production		
	Conversion efficiency of oil to gasoline or diesel	90.6%	Same as refining efficiency of crude oil to gasoline and diesel
Cellulosic Ethanol			
	a) Ethanol yield and coproducts		
	Yield	90 gal/dry ton	Wang et al. [33]
	co-produced electricity	2.28 kWh/gallon	Wang et al. [33]
	Cellulase	0.01 ton/dry ton of substrate	Dunn et al. [42]
	Yeast	0.00249 ton/dry ton of substrate	Dunn et al. [42]
	b) Land use change (LUC)		
	CO_2 Emissions from LUC (domestic)	-18 g/gallon of ethanol	Mueller et al. [34]
	CO_2 Emissions from LUC (foreign)	-78 g/gallon of ethanol	Mueller et al. [34]

Renewable Natural Gas from landfill (LFG)			
	RNG Processing Efficiency	94.4%	Mintz et al. [43]
	NG Processing CH4 Leakage	2%	Han et al. [39]
	NG Small Scale Liquefaction Efficiency (powered by RNG)	89%	Mintz et al. [43]
	Inclusion of LFG Flaring Emission Credit	yes	
	a) NG T&D		
	NG pipeline energy use	450 Btu/ton-mi	
	NG loss rate	0.45%	Burnham et al. [32]
	b) NG compression		
	Electrical Compression efficiency	97.3%	Brinkman et al. [26]
Electricity for hydrogen production			
	Electricity generation mix for electrolysis	100% renewable	
Electricity for PHEVs and BEVs			
	Electricity for recharging plug-in vehicles	100% renewable	

Table A3. Key assumptions for various vehicle technologies in 2010 and 2030 timeframes

Vehicle Technology	**Fuel Economy* (Adjusted from urban and highway test cycles to on-road performance)**	
	Model Year 2010	**Model Year 2025 for Year 2030 Simulation**
Baseline gasoline ICEV miles per gallon (MPG)	26.3, Weibull distribution (Shape: 2.90 Scale: 9.78, Location: 17.6)	33.2
Fuel Economy Ratio for other vehicles in miles per gasoline-gallon equivalent (MPGGE) relative to baseline gasoline ICEV MPG		
E85 ICEV	100%	105%
CNG ICEV	96%	100%
Diesel ICEV	120%	112%
Gasoline HEV	141%	142%
H_2 FCEV	183%	179%
BEV70	338%	330%
BEV210	260%	302%
PHEV 10 (power-split)		
Charge depletion (CD) electricity consumption (Wh/mi)	213	203
CD fuel consumption (Btu/mi)	1,201	822
CD distance (mi)	12	10
Charge sustain (CS) fuel economy ratio	143%	140%
CD fuel economy ratio	227%	229%
CD vehicle miles travelled (VMT) share	25%	25%
PHEV 28 (EREV)		
CD electricity consumption (Wh/mi)	349	316
CD fuel consumption (Btu/mi)	2	7
CD distance (mi)	29	29
CS fuel economy ratio	138%	122%
CD fuel economy ratio	367%	319%
CD VMT share	50%	50%

*Fuel economies were estimated through a modeling and simulation exercise that drew on projections of future technical feasibility for vehicle subsystems (engines, batteries, traction drives, lightweighting, etc.). The technical feasibility for each individual vehicle subsystem was estimated by a combined team of industry, government, and national laboratory experts, after which a modeling and simulation exercise was used to create virtual vehicles, the fuel economies of which were estimated based on virtual vehicle performance over standard EPA drive cycles.

Vehicle Technology	**Vehicle Parameters and Composition****	
	Model Year 2010	**Model Year 2025 for Year 2030 Simulation**
Gasoline ICEV		
Vehicle Weight (lb)	3,094, Logistics (Mean: 3,094, Scale: 185)	2,815
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc.)	80.54%	79.40%
Powertrain	12.90%	13.47%
Transmission system	5.35%	5.88%
Battery	1.07%	1.18%
Traction motor	0.00%	0.00%
Generator	0.14%	0.08%
Electronic controller	0.00%	0.00%
Diesel ICEV		
Vehicle weight (lb)	3,219	2,949
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc.)	77.40%	75.78%
Powertrain	15.62%	16.67%
Transmission system	5.14%	5.61%
Battery	1.71%	1.87%
Traction motor	0.00%	0.00%
Generator	0.14%	0.07%
Electronic controller	0.00%	0.00%
HEV		
Vehicle weight (lb)	3,355	3,010
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc..)	73.27%	73.14%
Powertrain	10.12%	10.69%
Transmission system	4.93%	5.49%
Battery	3.61%	4.39%
Traction motor	6.64%	4.91%
Generator	0.00%	0.00%
Electronic controller	1.43%	1.37%

PHEV10		
Vehicle weight (lb)	3,394	3,010
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc..)	72.44%	73.14%
Powertrain	10.07%	10.77%
Transmission system	4.87%	5.49%
Battery	4.65%	4.31%
Traction motor	6.50%	4.91%
Generator	0.00%	0.00%
Electronic controller	1.47%	1.37%
PHEV 28		
Vehicle weight (lb)	3,893	3,395
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc..)	63.15%	64.85%
Powertrain	8.61%	9.48%
Transmission system	4.25%	4.87%
Battery	11.63%	11.05%
Traction motor	10.53%	8.12%
Generator	0.00%	0.00%
Electronic controller	1.83%	1.64%
BEV70		
Vehicle weight (lb)	3,761	3,212
Lifetime VMT of a vehicle (miles)	110,000	110,000
Component composition, % by wt.		
Glider (chassis, body, etc.)	64.78%	67.85%
Powertrain	0.00%	0.00%
Transmission system	4.40%	5.15%
Battery	21.97%	18.55%
Traction motor	6.33%	5.70%
Generator	0.00%	0.00%
Electronic controller	2.52%	2.76%
BEV210		
Vehicle weight (lb)	5,986	4,344
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc.)	40.70%	50.18%
Powertrain	0.00%	0.00%
Transmission system	2.76%	3.81%
Battery	47.88%	38.84%
Traction motor	6.74%	5.03%
Generator	0.00%	0.00%
Electronic controller	1.91%	2.14%
FCEV		
Vehicle weight (lb)	3,885	3,266
Lifetime VMT of a vehicle (miles)	160,000	160,000
Component composition, % by wt.		
Glider (chassis, body, etc.)	62.71%	66.73%
Powertrain	21.91%	16.67%
Transmission system	4.26%	5.06%
Battery	3.20%	4.73%
Traction motor	5.56%	4.25%
Generator	0.00%	0.00%
Electronic controller	2.37%	2.55%

** Vehicle lightweighting was assumed to be achieved through a downsizing of vehicle subsystems. Though the relative decrease in size of vehicle subsystems was unique to each subsystem (that is, the portion by which each subsystem decreased in size was unique to each subsystem), the material composition of vehicle subsystems was assumed not to change, and, as such, is constant from Model Year 2010 through Model Year 2025.