ANL/ESD-16/7
Rev. 1

Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies

Energy Systems Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via DOE's SciTech Connect (http://www.osti.gov/scitech/).

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

ANL/ESD-16/7
Rev. 1

Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies

Amgad Elgowainy,[1] Jeongwoo Han,[1] Jacob Ward,[2] Fred Joseck,[2]
David Gohlke,[2] Alicia Lindauer,[2] Todd Ramsden,[3] Mary Biddy,[3]
Marcus Alexander,[4] Steven Barnhart,[5] Ian Sutherland,[6]
Laura Verduzco,[7] and Timothy J. Wallington[8]

[1]Argonne National Laboratory
[2]United States Department of Energy
[3]National Renewable Energy Laboratory
[4]Electric Power Research Institute
[5]FCA US LLC
[6]General Motors
[7]Chevron Corporation
[8]Ford Motor Company

September 2016

U.S. DRIVE Cradle-to-Grave Working Group members contributed to this report in a variety of ways, ranging from full-time work in multiple study areas to involvement on a specific topic, to drafting and reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with all of the assumptions, analysis, statements, and findings in the report. Any views and opinions expressed in the report are those of the authors and do not necessarily reflect those of Argonne National Laboratory, Chevron Corporation, the Electric Power Research Institute, Exxon Mobil Corporation, FCA US LLC, Ford Motor Company, General Motors, the National Renewable Energy Laboratory, Phillips 66 Company, Shell Oil Products US, or the U.S. Department of Energy.

CONTENTS

Notation ..... **xiii**

Acknowledgments ..... **xvii**

Executive Summary ..... **xviii**

1 Introduction **1**

1.1 Climate and Policy Context 1

1.2 Previous LCA and C2G Work 2

1.3 Overview of the Present C2G Study 3

1.4 Report Organization 5

1.5 References for Section 1 5

2 Overview of Methodology **8**

2.1 Study Scope, Definitions and Major Assumptions 8

2.2 Approach of Greenhouse Gas Emissions and Energy Use LCA 9

2.3 Vehicle Modeling Approach 10

2.4 Fuel Modeling Approach 11

2.5 References for Section 2 12

3 Vehicle-Fuel Pathway Selection and Vehicle Technologies **13**

3.1 Vehicle-Fuel Pathways 13

3.2 Description of Selected Vehicle Technologies 13

3.3 Technology Readiness Levels (TRLs) 15

3.4 References for Section 3 18

4 Fuel Pathways: GHG Assumptions and Data Sources **20**

4.1 Petroleum Pathways 20

4.1.1 Crude Production 21

4.1.2 GHG Emissions in Oil Fields 21

4.1.3 Crude Refining 23

4.2 Natural Gas Pathway 24

4.3 Biofuels Pathways 25

4.3.1 Corn Ethanol 25

4.3.2 Corn Stover Ethanol 26

4.3.3 Soybeans to Fatty Acid Methyl Ester and Hydroprocessed Renewable Diesel 28

4.3.4 Land Use Change from Biofuel Production 31

4.3.5 Pyrolysis of Cellulosic Biomass 32

4.4 Hydrogen Pathways 34
4.4.1 Steam Methane Reforming of Natural Gas 35
4.4.2 Water Electrolysis 35
4.4.3 Biomass Gasification 35
4.4.4 Hydrogen Delivery (Transmission, Distribution, and Refueling) 35
4.5 Gas-To-Liquid (GTL) Pathways 37
4.6 Electricity Pathways 37
4.7 Changes to Default Estimates from GREET 2014 38
4.8 References for Section 4 39
5 Fuel Pathways: Cost Assumptions and Data Sources 45
5.1 Approach, Assumptions, and Summary of Fuel Costs 45
5.2 Transportation Fuel Price Estimates from AEO 2015 47
5.3 Pyrolysis Fuels 48
5.4 Future Technology Diesel Fuels (HRD, FAME, GTL/FTD) 48
5.4.1 Hydroprocessed Renewable Diesel (HRD) Pathway 49
5.4.2 Fatty Acid Methyl Ester (FAME) Pathway 49
5.4.3 Gas-To-Liquid Fischer-Tropsch Diesel (GTL FTD) Pathway 49
5.5 Ethanol (E85) from Corn Stover 50
5.6 Electricity 51
5.7 Hydrogen Fuel 51
5.8 References for Section 5 53
6 Vehicle Fuel Consumption and Cost Assumptions 56
6.1 Autonomie Summary 56
6.2 Vehicle Components Sizing 57
6.3 Fuel Economy and Electricity Consumption 58
6.4 Vehicle Weight and Composition 61
6.4.1 Advanced Battery Cost Assumptions 63
6.5 Vehicle Cost 65
6.6 References for Section 6 68
7 Vehicle Production Pathways 70
7.1 System Boundary for Vehicle Production Pathways 70
7.2 Material Composition for Each Component 71
7.3 Key Material for Vehicle Production Pathways 76
7.3.1 Steel Production Pathways 76
7.3.2 Cast Iron Production Pathway 77

7.3.3 Aluminum Production Pathway 77
7.3.4 Plastic and CFRP Production Pathways 81
7.3.5 Li-ion Battery Production Pathways 83
7.3.6 Other Key Materials Production Pathways 86
7.4 Vehicle Assembly, Disposal, and Recycling 87
7.5 References for Section 7 88
8 Cradle-to-Grave GHG Results and Sensitivity 92
8.1 Greenhouse Gas Emissions 92
8.2 Total Energy 93
8.3 References for Section 8 93
9 Levelized Cost of Driving Analysis 97
9.1 LCD Analysis Framework 97
9.2 LCD Results 98
9.3 LCD Sensitivity Results 100
9.4 Oil Price Sensitivity 104
9.5 References for Section 9 105
10 Cost of Avoided GHG Emissions 106
10.1 Analysis Framework 106
10.2 Cost of Avoided GHG Emissions: Current Technology Case 107
10.3 Cost of Avoided GHG Emissions: Future Technology Case 108
10.4 Sensitivity Analysis Cases 113
10.5 References for Section 10 117
11 Limitations and Future Implications 118
12 Conclusions 119
Appendix A: Description of Fuel Production Pathways: Key Stages and Parameters 121
Appendix B: Price and Efficiency Comparison of Modeled and Real-World Vehicles 135
Appendix C: GHG Emissions for Different Vehicle-Fuel Pathways 138
Appendix D: Sensitivity of GHG Emission Projections to Key Vehicle-Fuel Parameters 144
Appendix E: LCD Calculation Details and Examples 161
Appendix F: Comparison between Fuel Price Projections 164
Appendix G: Compilation of All References Used in this Report 169

FIGURES

ES-1 C2G GHG emissions of various vehicle-fuel pathways. xx

ES-2 LCD for CURRENT TECHNOLOGY cases xxi

ES-3 LCD for select FUTURE TECHNOLOGY, HIGH VOLUME cases xxi

ES-4 Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY cases, relative to the CURRENT TECHNOLOGY gasoline ICEV xxii

ES-5 Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case (2013$), relative to the FUTURE TECHNOLOGY gasoline ICEV xxiii

1 Combined fuel cycle and vehicle cycle activities included in C2G analysis 10

2 Technology readiness levels 16

3 Key stages and activities of the petroleum fuels pathway 20

4 Key stages and activities of the CNG pathway 24

5 Bio-ethanol pathway activities in GREET 26

6 Soybean pathways to produce FAME and HRD 28

7 Estimates for LUC contribution to GHG emissions from corn ethanol production 32

8 Liquid fuels production from cellulosic biomass via fast pyrolysis 33

9 Hydrogen production and delivery pathways 34

10 Summary of fuel cost results 47

11 Vehicle fuel economy ratio relative to CURRENT TECHNOLOGY gasoline ICEV assuming medium technology progress 62

12 Vehicle component weight results 63

13 Summary of low-volume vehicle costs from Tables 38 and 39. 67

14 GREET vehicle manufacturing cycle 70

15 Process for GREET vehicle manufacturing cycle analysis 71

16 Steel production steps 76

17 Wrought and cast aluminum production steps 79

18 Li-ion battery production material and energy flows in GREET 83

19 Potential GHG emissions reductions. 93

20 GHG emissions for biomass-based fuels 95

21 GREET results of energy consumption for all vehicle-fuel combinations 95

22 LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case 99

23 LCD by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case 99

24 3-year and 15-year LCD results by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case 101

25 3-year and 15-year LCD results by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case 101

26 Upper- and lower-bound LCD results by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case 102

27 Upper- and lower-bound LCD results by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case 102

28 LCD results for the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases, 5-year analysis window, 5% discount rate base case 103

29 LCD results for the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases, 15-year analysis window, 5% discount rate case 103

30 Historical crude oil spot prices for Cushing, OK, West Texas Intermediate, 1991–2016, daily averages 104

31 Historical consumer gasoline prices, including taxes and retail markup, 1991–2016, weekly averages 105

32 Cost of avoided GHG emissions calculation 107

33 Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case, relative to the CURRENT TECHNOLOGY gasoline ICEV 109

34 Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case, relative to the FUTURE TECHNOLOGY gasoline ICEV 111

35 Range of CURRENT TECHNOLOGY case avoided GHG emissions results using 3 different analysis frameworks 114

36 Range of FUTURE TECHNOLOGY case avoided GHG emissions results using 3 different analysis frameworks 114

37 Cost of avoided GHG emissions for the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases, base case 115

38 Cost of avoided GHG emissions for the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases, 15-year lifetime analysis window 115

39 Effect of different LUC assumptions on the cost of avoided GHG emissions for the E85, FAME, and HRD pathways 116

A.1 Petroleum gasoline, diesel, and LPG fuel cycle 121

A.2 Corn ethanol fuel cycle 123

A.3 Bio-based gasoline and diesel production steps 125

A.4 FTD production from NG 126

A.5 FAME biodiesel production pathway from soybeans 127

A.6 HRD production pathway from soybeans 127

A.7 Cellulosic ethanol fuel cycle 129

A.8 CNG pathway 131

A.9 Grid electricity generation cycle 132

A.10 Hydrogen fuel pathways 134
A.11 Hydrogen production from biomass gasification 134
B.1 Fuel economy and price for midsize vehicles sold in 2015 136
B.2 Fuel economy and price for midsize ICEVs sold in 2015 137
C.1 Emissions for ICEV with gasoline sourced from petroleum and forest residue pyrolysis 138
C.2 Emissions for multiple gasoline, diesel, and NG ICEV pathways compared with gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains 139
C.3 Emissions for LPG ICEVs, E85 FFVs, and gasoline HEVs compared with gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains 140
C.4 Emissions for gasoline PHEV35 and H_2 FCEVs compared with gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains 141
C.5 Emissions for advanced BEV pathways compared with gasoline ICEV CURRENT TECHNOLOGY and efficiency gains 142
C.6 Vehicle cycle GHG emissions by vehicle component for the CURRENT TECHNOLOGY case 143
C.7 Vehicle cycle GHG emissions by vehicle component for the FUTURE TECHNOLOGY case 143
D.1 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY gasoline ICEV 144
D.2 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY diesel ICEV 144
D.3 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY diesel ICEV – GTL FTD 145
D.4 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY LPG ICEV 145
D.5 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY CNG ICEV 146
D.6 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY E85 FFV 146
D.7 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY gasoline HEV 147
D.8 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY PHEV10 147
D.9 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY PHEV35 148
D.10 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY H_2 FCEV 148
D.11 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY BEV90 149
D.12 Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY BEV210 149

D.13 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline ICEV – forest residue pyrolysis gasoline 150

D.14 Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – forest residue pyrolysis diesel 150

D.15 Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – soybean-based HRD 151

D.16 Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – soybean-based B20 151

D.17 Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – FTD with CCS 152

D.18 Changes in GHG emissions for FUTURE TECHNOLOGY E85 FFV – corn stover-based ethanol 152

D.19 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline HEV – forest residue pyrolysis gasoline 153

D.20 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV10 – forest residue pyrolysis gasoline + solar/wind electricity 153

D.21 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV10 – forest residue pyrolysis gasoline + ACC electricity 154

D.22 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV10 – forest residue pyrolysis gasoline + ACC electricity with CCS 154

D.23 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV35 – forest residue pyrolysis gasoline + solar/wind electricity 155

D.24 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV35 – forest residue pyrolysis gasoline + ACC electricity 155

D.25 Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV35 – forest residue pyrolysis gasoline + ACC electricity with CCS 156

D.26 Changes in GHG emissions for FUTURE TECHNOLOGY H_2 FCEV – electrolysis with solar/wind electricity 156

D.27 Changes in GHG emissions for FUTURE TECHNOLOGY H_2 FCEV – NG SMR with CCS 157

D.28 Changes in GHG emissions for FUTURE TECHNOLOGY H_2 FCEV – biomass gasification using poplar 157

D.29 Changes in GHG emissions for FUTURE TECHNOLOGY BEV90 – solar/wind electricity 158

D.30 Changes in GHG emissions for FUTURE TECHNOLOGY BEV90 – ACC electricity 158

D.31 Changes in GHG emissions for FUTURE TECHNOLOGY BEV90 – ACC electricity with CCS 159

D.32 Changes in GHG emissions for FUTURE TECHNOLOGY BEV210 – solar/wind electricity 159

D.33 Changes in GHG emissions for FUTURE TECHNOLOGY BEV210 – ACC electricity 160

D.34 Changes in GHG emissions for FUTURE TECHNOLOGY BEV210 – ACC electricity with CCS 160

F.1 LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY case using AEO 2014 cost projections 165

F.2 LCD by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case using AEO 2014 cost projections 166

F.3 Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case, relative to the CURRENT TECHNOLOGY gasoline ICEV, using AEO 2014 cost projections 167

F.4 Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case, relative to the FUTURE TECHNOLOGY gasoline ICEV, using AEO 2014 cost projections 168

TABLES

ES-1 Fuel production pathways considered in this C2G analysis xix

1 Fuel production pathways considered in this C2G analysis 4

2 Vehicle-fuel combinations considered in this C2G analysis 5

3 Vehicle scale assumptions by technology 9

4 Overview of vehicle and fuel cost models and data sources 12

5 Comparison of naming conventions in this report and the Autonomie study 14

6 Results of the TRL analysis 17

7 Crude oil sources in the U.S. 21

8 Energy intensities of extraction and separation, upgrading, and crude transportation for the four oil sands pathways, compared to those of the U.S. conventional crudes pathway 21

9 Ratios of CO_2 to CH_4 volume in emissions from petroleum production fields 22

10 Properties of gas flared and vented during crude oil production 22

11 VFF CH_4 and CO_2 emission factors from U.S. crude oil production 23

12 Refinery Process Fuel Use for Major Fuel Products 23

13 Summary of CH_4 emission factors by activity in GREET 2014 25

14 GREET and EPA CH_4 leakage rate based on NG throughput by stage 25

15 Assumptions for the corn ethanol production pathway used in GREET 2014 27

16 Assumptions for the corn stover ethanol production pathway 27

17 Soybean production in 19 program states 28

18 Fertilizers and chemicals applied to soybean-planted acres in 19 program states 28

19 Fertilizer and chemical application rates for soybean farming 29

20 Soybean farming energy inputs 29

21 Assumptions for HRD production from soybeans 29

22 Soybean crushing and soy oil transesterification assumptions 30

23 Assumptions about the production of fast-pyrolysis-based liquid fuels from forest residue 34
24 Energy efficiency of hydrogen production via SMR 35
25 Hydrogen production efficiency and process fuel shares for gasification of woody biomass 36
26 U.S. average generation mix in 2013 and 2030 38
27 Energy efficiencies and generation technology shares of thermal EGUs 38
28 2014 U.S. average generation mix from AEO 2015 38
29 NG recovery and processing electricity consumption 39
30 Common assumptions used in fuel cost modeling 45
31 Fuel cost assumptions 46
32 AEO 2015 electricity price inputs and BEV fuel costs for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases 52
33 Hydrogen pathway costs for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases 53
34 Test cycle and on-road adjusted fuel economy and electricity consumption for gasoline, CNG, and diesel ICEVs; gasoline HEVs; H_2 FCEVs; and BEVs 90 and 210 59
35 Autonomie-modeled test cycle and on-road adjusted fuel economy and electricity consumption for the gasoline PHEV10 and PHEV35 60
36 Combined fuel economy and electricity consumption adjusted for on-road performance 61
37 Vehicle weight and composition results 64
38 Vehicle costs used in this study from the Autonomie model 66
39 Low-volume vehicle costs for vehicle technologies used in this study 67
40 Subcomponent weight distribution 72
41 Material composition of components and subcomponents, except for battery 73
42 Material composition aggregated by component except for battery 74
43 Material composition of battery 75
44 Process assumptions for steel production 78
45 Process assumptions for cast iron production. 79
46 Process assumptions for aluminum production 80
47 Energy use for plastic resin production and share of individual plastic in a vehicle 81
48 Plastic transformation process assumptions 82
49 Li-ion battery production process assumptions 85

50 Process assumptions for lead, glass, rubber, and copper 87
51 Vehicle assembly, disposal, and recycling process assumptions 88
52 GHG emissions for the FUTURE TECHNOLOGY reductions shown in Figure 19 94
53 Total energy consumed, as shown in Figure 21 96
54 Key data used in the cost of avoided GHG emissions metric for the CURRENT TECHNOLOGY, HIGH VOLUME case 108
55 Key data used in the cost of avoided GHG emissions metric for the FUTURE TECHNOLOGY, HIGH VOLUME case 110
56 Cost of avoided GHG emissions results by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases, relative to their respective gasoline ICEVs 112
B.1 Fuel economy and MSRPs for MY2015 midsize vehicles sold in 2015 in the United States 135
E.1 Sample calculations for the LCD fuel-cost component and net vehicle cost 162
E.2 Sample data for the LCD vehicle-cost component showing the annual vehicle costs on an NPV basis 163
E.3 LCD cost components for two examples 163
F.1 Key differences between AEO 2014 and AEO 2015 164

NOTATION

ACRONYMS AND INITIALISMS

ABS	acrylonitrile butadiene styrene
ACC	advanced combined cycle
ADR	assembly, disposal, and recycling
AEO	Annual Energy Outlook
AFDC	Alternative Fuels Data Center
ASCM	Automotive System Cost Model
ASTM	American Society of Testing and Materials
BatPaC	Battery Performance and Cost [model]
BEA	Bureau of Economic Analysis
BEV	battery electric vehicle
BMS	battery management system
BNEF	Bloomberg New Energy Finance
BOL	beginning of life
BSI	British Standards Institution
C2G	cradle-to-grave
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use Change from Biofuels
CCS	carbon capture and storage
CD	charge depleting
CFRP	carbon fiber reinforced plastic
CHP	combined heat and power
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO_2e	CO_2-equivalent
COG	coke oven gas
COLE	Carbon Online Estimator
CS	charge sustaining
DGS	distillers' grains and solubles
DOE	Department of Energy
EC	European Community
EGU	electric generating unit
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EOL	end of life
EPA	Environmental Protection Agency
EPDM	ethylene propylene diene monomer
EREV	extended-range electric vehicle
EU	European Union

FAME	fatty acid methyl ester
FAPRI	Food and Agricultural Policy Research Institute
FASOM	Forest and Agricultural Sector Optimization Model
FCEV	fuel cell electric vehicle
FFV	flexible fuel vehicle
GHG	greenhouse gas
GPO	Government Printing Office
GPPS	general purpose polystyrene
GREET	Greenhouse gas, Regulated Emissions, and Energy use in Transportation [model]
GTAP	Global Trade Analysis Project
GTL FTD	gas-to-liquid Fischer-Tropsch diesel
GVW	gross vehicle weight
H2A	Hydrogen Analysis
H_2 FCEV	hydrogen FCEV
HDPE	high-density polyethylene
HDSAM	Hydrogen Delivery Scenario Analysis Model
HEV	hybrid electric vehicle
HIPS	high-impact polystyrene
HRD	hydroprocessed renewable diesel
HVAC	heating, ventilation, and air conditioning
HWFET	Highway Federal Emissions Test
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	internal rate of return
LCA	lifecycle analysis
LCD	levelized cost of driving
LCFS	[California] Low Carbon Fuel Standard
LDPE	low-density polyethylene
LDV	light-duty vehicles
LHV	lower heating value
LLDPE	linear low-density polyethylene
LMO	lithium manganese oxide
LPG	liquefied petroleum gas
LUC	land use change
MIT	Massachusetts Institute of Technology
MSRP	manufacturer's suggested retail price
MY	model year
MYPP	Multi-Year Progress Plan

NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NBB	National Biodiesel Board
NCA	nickel cobalt aluminum oxide
NG	natural gas
NHTSA	National Highway Traffic Safety Administration
NMC	nickel manganese cobalt oxide
NMP	N-methyl-2-pyrrolidone
NPV	net present value
NREL	National Renewable Energy Laboratory
PADD	Petroleum Administration for Defense District
PAN	polyacrylonitrile
PC	polycarbonate
PEM	polymer electrolyte membrane
PET	polyethylene terephthalate
PHEV	plug-in hybrid electric vehicle
PP	polypropylene
PUR	polyurethane
PV	photovoltaic
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
R&D	research and development
RED	[EU] Renewable Energy Directive
RFS	Renewable Fuel Standard
RPE	retail price equivalent
SAE	Society for Automotive Engineers International
SBR	styrene-butadiene rubber
SCO	synthetic crude oil
SI	spark-ignition
SMR	steam methane reforming
SOC	soil organic carbon
TEA	techno-economic analysis
TRL	technology readiness level
TTW	tank-to-wheels
UDDS	Urban Dynamometer Driving Schedule
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VFF	vented, flaring, and fugitive
VMT	vehicle miles travelled
VOC	volatile organic carbon
WTT	well-to-tank
WTW	well-to-wheels
ZEV	Zero-Emission Vehicle

UNITS OF MEASURE

bbl	barrel(s)
Btu	British thermal unit
°C	degree(s) Celsius
°F	degree(s) Fahrenheit
g	gram(s)
gal	gallon(s)
gge	gallon gasoline equivalent
GJ	gigajoule(s)
in.	inch(es)
kg	kilogram(s)
kJ	kilojoule(s)
kWh	kilowatt-hour(s)
L	liter(s)
lb	pound(s)
m^3	cubic meter(s)
mAh	milliampere-hour(s)
mi	mile(s)
MJ	megajoule(s)
MMBtu	million Btu
mpg	mile(s) per gallon
mpgge	miles per gallon gasoline equivalent
mph	mile(s) per hour
ppm	part(s) per million
psi	pound(s) per square inch
sec	second(s)
ton	short ton (2,000 lb)
tonne	metric ton (1,000 kg)
V	volt(s
Wh	watt hour(s)

ACKNOWLEDGMENTS

The research effort by Argonne National Laboratory was supported by the Fuel Cell Technologies Office and the Vehicle Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy under Contract Number DE-AC02-06CH11357.

The authors give primary credit for this report to the U.S. DRIVE Partnership Cradle-to-Grave Working Group. U.S. DRIVE, which stands for United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability, is a government-industry partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company, and General Motors; five energy companies – BP America, Chevron Corporation, Exxon Mobil Corporation, Phillips 66 Company, and Shell Oil Products US; Tesla Motors; two utilities – Southern California Edison and Michigan-based DTE Energy; and the Electric Power Research Institute.

U.S. DRIVE Cradle-to-Grave Working Group members contributed to this report in a variety of ways, ranging from fulltime work in multiple study areas to involvement on a specific topic, or to drafting and reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with all of the assumptions, analysis, statements, and findings in the report. Any views and opinions expressed in the report are those of the authors and do not necessarily reflect those of Argonne National Laboratory, Chevron Corporation, Electric Power Research Institute, Exxon Mobil Corporation, FCA US LLC, Ford Motor Company, General Motors, National Renewable Energy Laboratory, Phillips 66 Company, Shell Oil Products US, or the U.S. Department of Energy.

Cradle-to-Grave Working Group Members

Marcus Alexander	Manager, Vehicle Systems Analysis	Electric Power Research Institute
Steven Barnhart	Manager, Government Collaborative Programs	FCA US LLC
Mary Biddy	Senior Research Engineer, Biomass Research	National Renewable Energy Laboratory
Eric M. Bunnelle	Advanced Fuels Advisor, Strategy & Planning	ExxonMobil Refining & Supply Company
Amgad Elgowainy	Life-Cycle Analysis Team Lead/Principal Energy Systems Analyst, Energy Systems Division	Argonne National Laboratory
David Gohlke	AAAS Science and Technology Policy Fellow, Vehicle Technologies Office	U.S. Department of Energy
Jeongwoo Han	Energy Systems Analyst, Energy Systems Division	Argonne National Laboratory
Fred Joseck	Systems Analysis Project Manager, Fuel Cell Technologies Office	U.S. Department of Energy
Amit Kapur	Senior Engineer, Technology	Phillips 66 Company
Alicia Lindauer	Technology Manager for Strategic Analysis, Bioenergy Technologies Office	U.S. Department of Energy
Todd Ramsden	Program Manager, Systems Engineering & Program Integration Office	National Renewable Energy Laboratory
Herie Soto	Technology Advisor – Hydrogen, Shell	Shell Oil Products US
Ian Sutherland	Research Staff Member, Global Energy Systems	General Motors
Laura Verduzco	Senior Planning Engineer, Chevron Energy Technology Company	Chevron Corporation
Timothy J. Wallington	Senior Technical Leader, Environmental Sciences	Ford Motor Company
Jacob Ward	Program Manager for Analysis, Vehicle Technologies Office	U.S. Department of Energy

EXECUTIVE SUMMARY

This study provides a comprehensive lifecycle analysis (LCA), or cradle-to-grave (C2G) analysis, of the cost and greenhouse gas (GHG) emissions of a variety of vehicle-fuel pathways, as well as the levelized cost of driving (LCD) and cost of avoided GHG emissions. This study also estimates the technology readiness levels (TRLs) of key fuel and vehicle technologies along the pathways. The C2G analysis spans a full portfolio of midsize light-duty vehicles (LDVs), including conventional internal combustion engine vehicles (ICEVs), flexible fuel vehicles (FFVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). In evaluating the vehicle-fuel combinations, this study considers both low-volume and high-volume "CURRENT TECHNOLOGY" cases (nominally 2015) and a high-volume "FUTURE TECHNOLOGY" lower-carbon case (nominally 2025–2030). For the CURRENT TECHNOLOGY case, low-volume vehicle and fuel production pathways are examined to determine costs in the near term.

The pathway approach selected for this study is not necessarily constrained by practical feedstock, economic, policy, and market considerations, though only pathways of sufficient technological readiness were included. This is in contrast with a scenario approach, which postulates a specific vehicle-fuel production pathway or a mix of pathways that factor in real or hypothetical/perceived feedstock, economic, policy, and market considerations. As such, this study strictly focuses on possible vehicle-fuel combination pathways (i.e., no scenario analysis was conducted). The fuel pathways considered in this study are shown in Table ES-1. The selected fuel pathways were constrained to those deemed to be scalable to at least approximately 10% of LDV fleet demand in the future.

The C2G greenhouse gas emissions evaluation was carried out by expanding and modifying the GREET™ (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model suite (2014 version) with inputs from industrial experts. This C2G GHG assessment includes both fuel and vehicle production life cycles. Cost assessments represent a final cost to the consumer, excluding tax on the final product (e.g., fuel sales tax) and/or credits (e.g., vehicle subsidies). Where available, current and future fuel cost estimates are from the 2015 DOE Energy Information Administration (EIA) Annual Energy Outlook (AEO). Otherwise, cost assessment is based on publicly available data and models, such as techno-economic analysis (TEA) models developed by DOE and its national laboratories, using a standard set of assumptions to ensure that evaluations are consistent across fuel pathways, although some of the biofuel pathways are evaluated based on external modeling and analysis reported in the literature.

The modeling of various vehicle technologies, current and future, included powertrain configuration, component sizing, cost, and fuel economy and was performed with the Autonomie model. Autonomie is a modeling package that uses performance attributes of vehicle components to size components for a given vehicle configuration and vehicle performance attributes (e.g., time to accelerate from 0–60 mph, maximum speed, etc.), and to simulate fuel economy over various driving cycles. These fuel economies served as an input for this analysis and are presented in Table 36 and Figure 11 in Section 6.3. The component sizes and vehicle fuel economy results were incorporated into the GREET model to evaluate GHG emissions of vehicle production and fuel cycles, respectively, while the vehicle costs were used to evaluate the LCD. This report uses Autonomie manufacturing cost estimates that assume production at volume; however, it is important to recognize that the initial manufacture of advanced powertrain vehicles is likely to incur additional costs beyond those estimated at large scale. Accordingly, low-volume vehicle cost estimates of the CURRENT TECHNOLOGY case provide context for the high-volume estimates by serving as an indication of the degree to which low-volume manufacturing could affect vehicle cost, LCD, and cost of abated carbon.

Table ES-1. Fuel production pathways considered in this C2G analysis

Fuel	CURRENT TECHNOLOGY Case	FUTURE TECHNOLOGY Case
Gasoline (E10)	U.S. average crude mix (blended with 10% corn ethanol)	Pyrolysis of forest residue (no ethanol blending)
Diesel	U.S. average crude mix	Pyrolysis of forest residue
		Hydroprocessed renewable diesel (HRD) from soybeans
		20% fatty acid methyl ester (FAME) drop-in bio-based diesel (B20) from soybeans
		Gas-to-liquid Fischer-Tropsch diesel (GTL FTD)
CNG	U.S. average of conventional and shale gas mix	—
LPG	75% from U.S. conventional and shale gas mix and 25% from U.S. average crude mix	—
Ethanol (E85)	85% corn ethanol (blended with 15% petroleum gasoline blendstock)	85% cellulosic from corn stover (blended with 15% petroleum gasoline blendstock)
Hydrogen	Centralized production from steam methane reforming (SMR)	Electrolysis from wind
		Biomass (poplar) gasification
		Natural gas SMR with carbon capture and storage (CCS)
Electricity	EIA AEO U.S. average electricity generation mix in 2014	Natural gas advanced combined cycle (ACC)
		Natural gas ACC w/ CCS
		Wind
		Solar photovoltaic

Figure ES-1 shows that larger GHG reductions for LDVs are achieved with both low-carbon fuels and vehicle efficiency improvements. The black lines in the figure represent the C2G GHG emissions for the CURRENT TECHNOLOGY case. For this case, conventional gasoline ICEVs are modeled to have C2G GHG emissions of slightly more than 450 g CO_2e/mile (grams of CO_2 equivalent per mile). Gasoline HEVs can reduce C2G GHG emissions to below 350 g CO_2e/mi, as can other advanced vehicle technologies, such as PHEVs, BEVs, and FCEVs. The red lines show that lower GHG emissions can be realized in the FUTURE TECHNOLOGY case across all vehicle platforms due to vehicle efficiency gains, such as lightweighting and higher powertrain efficiency. Such vehicle technology improvements lead to C2G GHG emissions of about 350 g CO_2e/mi for gasoline ICEVs and below 250 g CO_2e/mi for HEVs, PHEVs, FCEVs, and BEVs. Combining vehicle efficiency gains with low-carbon fuels (lines at head of each arrow), the GHG reductions generally more than double compared to vehicle gains alone. For example, gasoline ICEVs running on gasoline developed from pyrolysis of forest residues are modeled to have C2G GHG emissions of about 140 g CO_2e/mi, while FCEVs running on hydrogen produced from biomass gasification have emissions of about 115 g CO_2e/mi. BEVs running on wind electricity and FCEVs running on hydrogen from wind electricity have C2G GHG emissions of about 50 g CO_2e/mi or less.

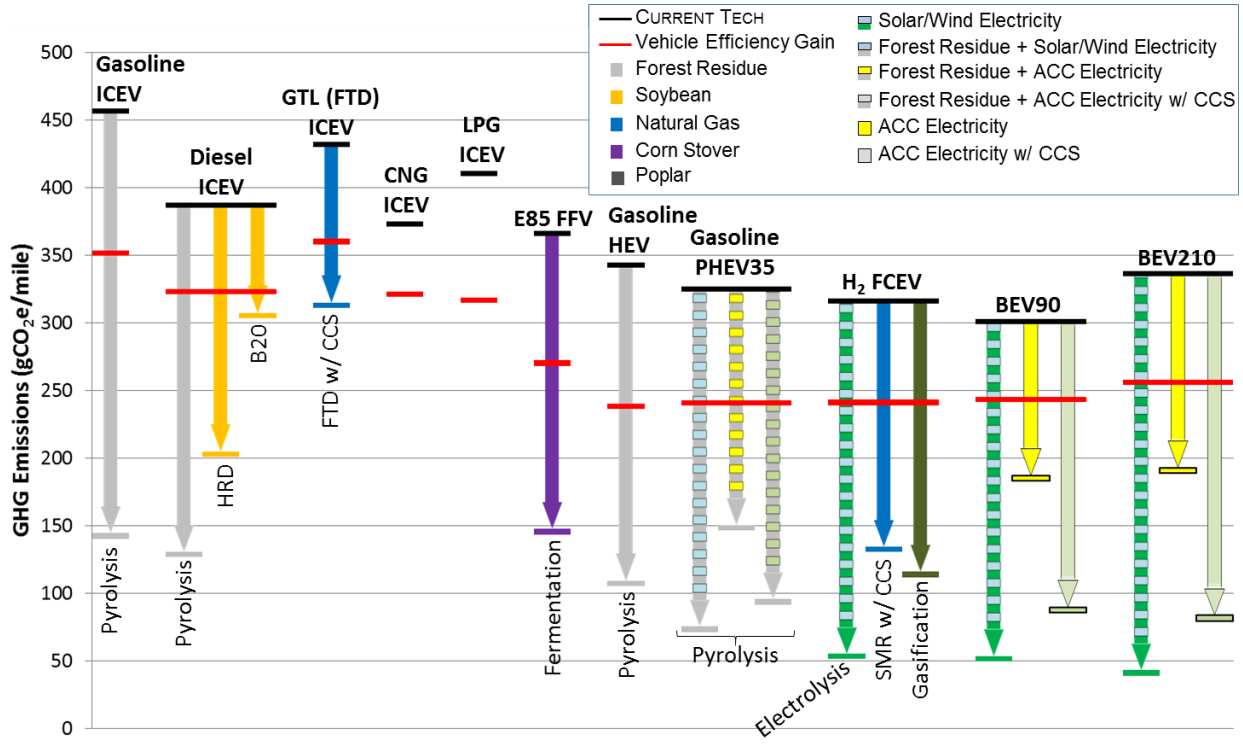

Figure ES-1. C2G GHG emissions of various vehicle-fuel pathways. Analysis was performed using GREET2014, and vehicle and fuel pathways are constrained to those deemed scalable to approximately 10% of the LDV fleet.

Figures ES-2 and ES-3 show the LCD for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, respectively. LCD is defined as the sum of the amortized net vehicle cost per mile (after considering residual resale value) and the fuel cost per mile. The uncertainty bars reflect the range of vehicle and fuel costs considered for analysis. The figures show that vehicle cost is the major (60–90%) and fuel cost the minor (10–40%) component of the LCD when projected at volume and that many alternative vehicles and/or fuels cost significantly more than conventional gasoline vehicles for the CURRENT TECHNOLOGY, HIGH VOLUME case, even when cost is projected for high-volume production. Modeling of the CURRENT TECHNOLOGY, HIGH VOLUME case (over a 15-year vehicle lifetime) shows LCD below $0.30/mi for the more established vehicle-fuel pathways, including conventional gasoline and diesel ICEVs, HEVs, and E85- and CNG-fueled vehicles. In the CURRENT TECHNOLOGY, HIGH VOLUME case, emerging advanced technology vehicles exceed these costs, with early commercialization technologies, such as FCEVs and BEVs, having significantly higher LCDs compared to conventional gasoline ICEVs. Additionally, a CURRENT TECHNOLOGY, LOW VOLUME case was analyzed, showing an increase in the LCD when assuming low-volume production of vehicles or delivery of fuel for H_2. Levelized costs of advanced technologies in FUTURE TECHNOLOGY, HIGH VOLUME case are reduced, reflecting estimated research and development (R&D) outcomes. In the FUTURE TECHNOLOGY, HIGH VOLUME case, the LCD for gasoline ICEVs (over a 15-year lifetime) remains at $0.26/mi, but many vehicle-fuel pathways show improvement with costs within a 25% increase over gasoline ICEVs. Early-commercialized advanced technology vehicles, such as PHEVs, FCEVs, and BEVs in particular, are estimated to have significantly improved levelized costs.

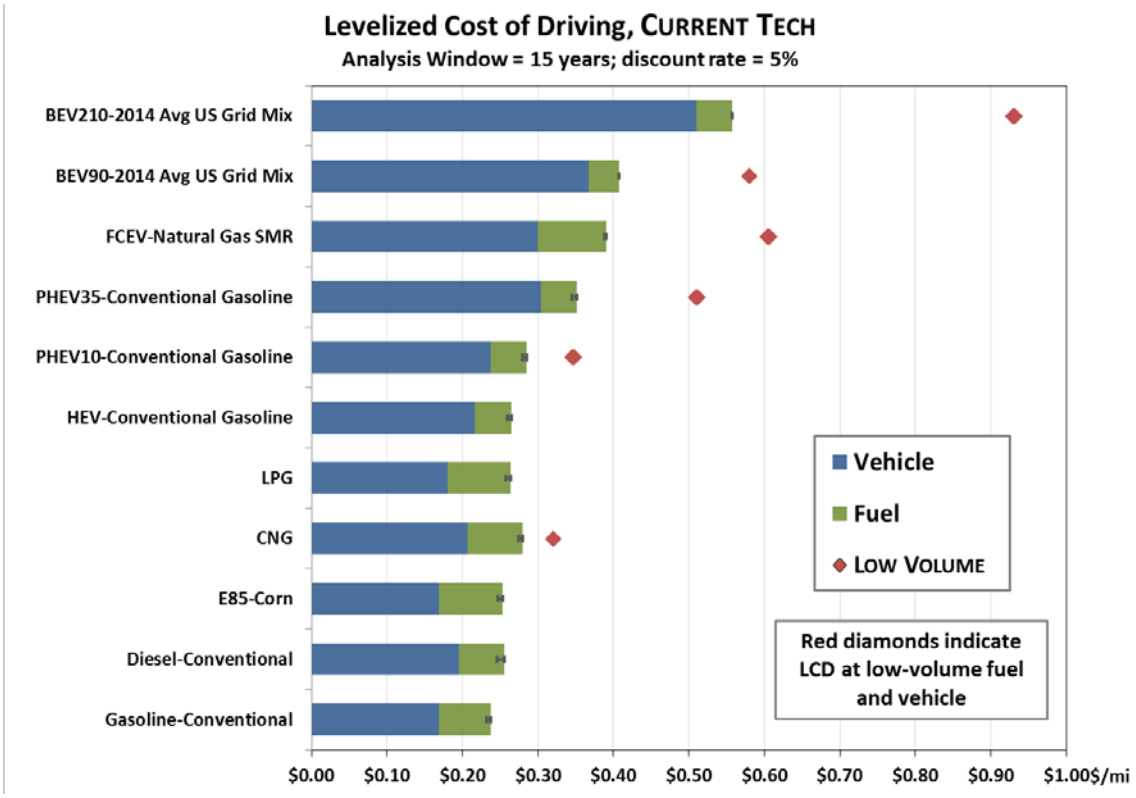

Figure ES-2. LCD for CURRENT TECHNOLOGY cases (2013$)

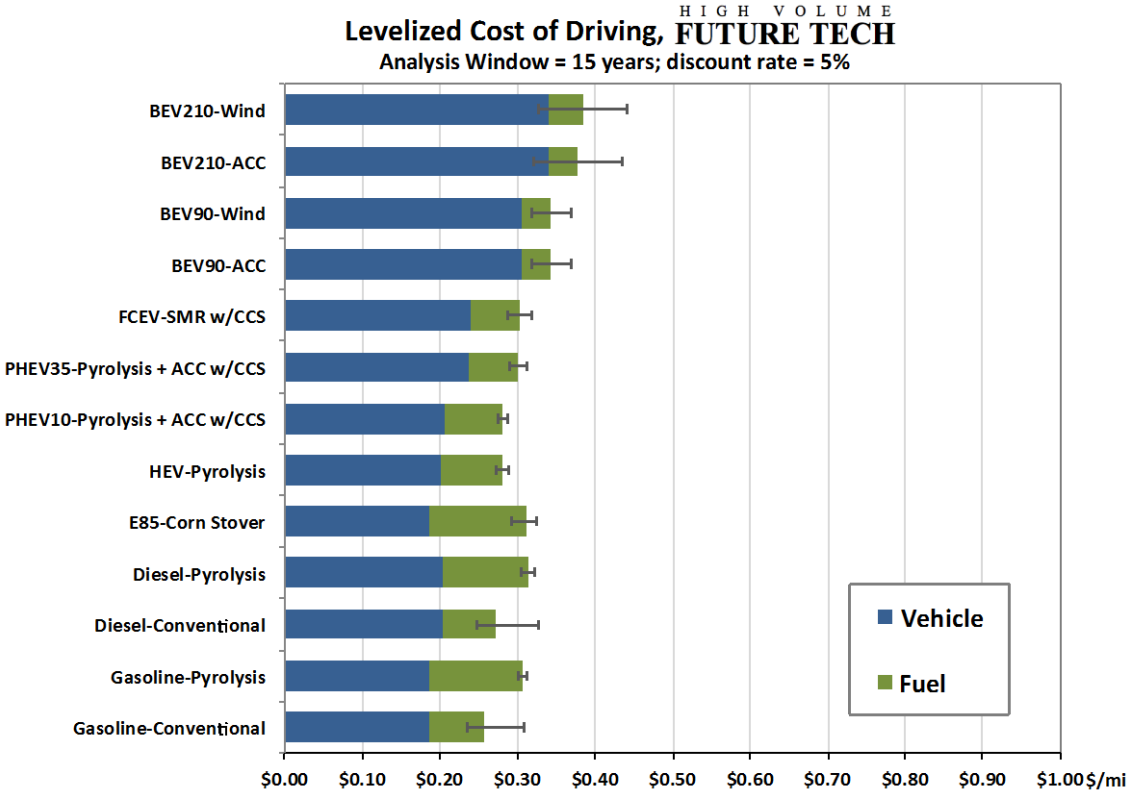

Figure ES-3. LCD for select FUTURE TECHNOLOGY, HIGH VOLUME cases (2013$)

Figures ES-4 and ES-5 show the costs associated with avoided GHG emissions (in U.S. dollars per metric ton, or tonne, of GHG emissions, measured on a CO_2e basis) of various vehicle-fuel pathways for CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, respectively. The darker bars in the figures consider a full 15-year vehicle lifetime, while the lighter bars represent the sensitivity for a 3-year ownership period. The black diamonds represent the cost of avoided GHG emissions in the CURRENT TECHNOLOGY, LOW VOLUME case assuming a 15-year vehicle lifetime. For the CURRENT TECHNOLOGY, HIGH VOLUME case considered over a 15-year lifetime, with the exception of the BEV210, the cost of avoided GHG emissions for most vehicle-fuel pathways falls within the range of \$100/tonne CO_2e to \$1,100/tonne CO_2e. For FUTURE TECHNOLOGY, HIGH VOLUME case considered over a 15-year lifetime, the projected costs of avoided GHG emissions are in the range of approximately \$80–\$500/tonne CO_2e, with the exception of diesel fuel pathways. Hybrid and plug-in hybrid vehicle platforms offer the lowest modeled costs of avoided GHG emissions, with costs of approximately \$90–\$170/tonne CO_2e measured over the vehicle's full 15-year lifetime. The interpretation of GHG abatement costs embodied in the "cost of avoided GHG emissions" metric has limitations, since the vehicle technologies considered in this analysis differ not only in their lifetime GHG emissions but also in other important attributes, such as local air quality-related emissions, reliance on different fuels (e.g., petroleum, natural gas, ethanol, hydrogen, electricity), and functionality (e.g., more limited range and longer refueling times for BEVs). In this report, the costs of avoided GHG emissions are a direct measure of additional costs associated with reducing emissions in transportation and are not commensurate with broader aspects, such as a social cost of carbon, e.g., the monetized damages associated with a marginal increase in carbon emissions.

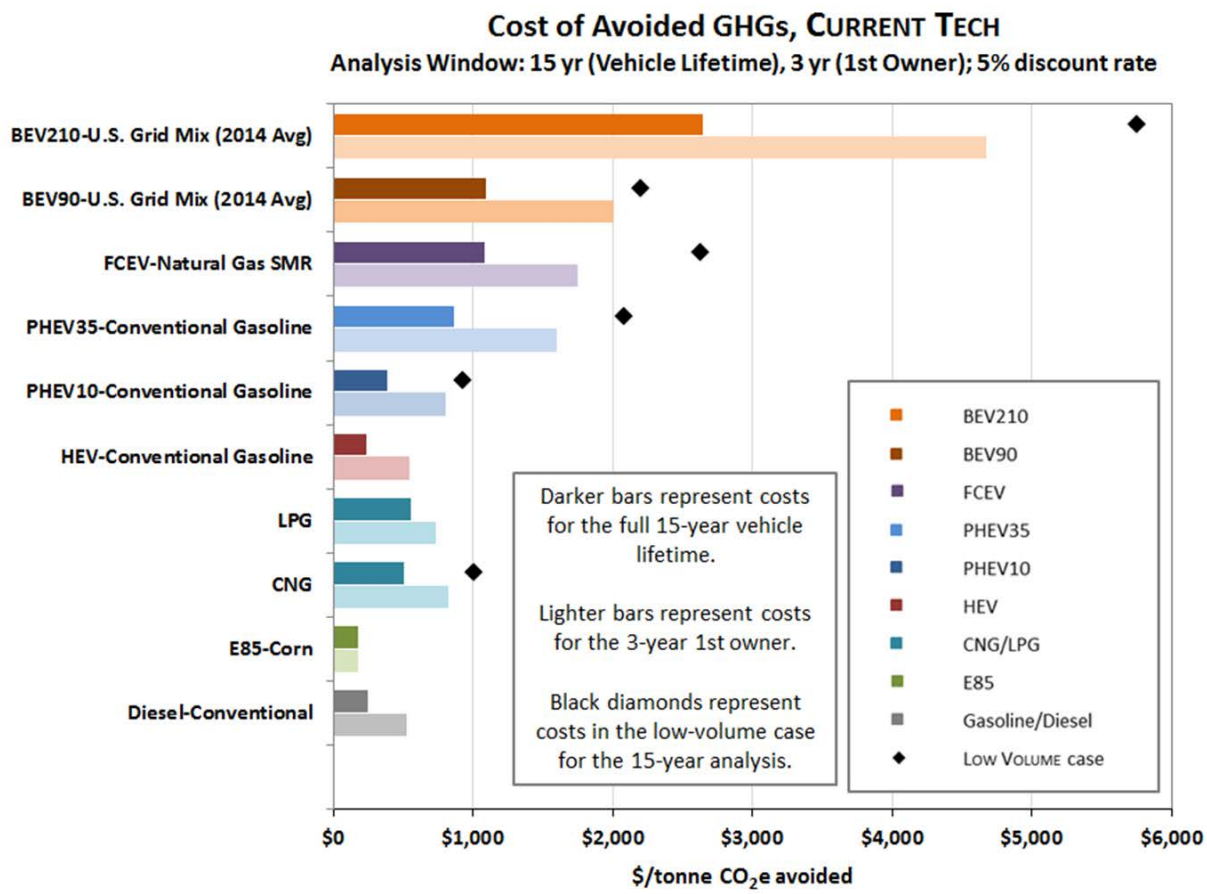

Figure ES-4. Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY cases (2013\$), relative to the CURRENT TECHNOLOGY gasoline ICEV

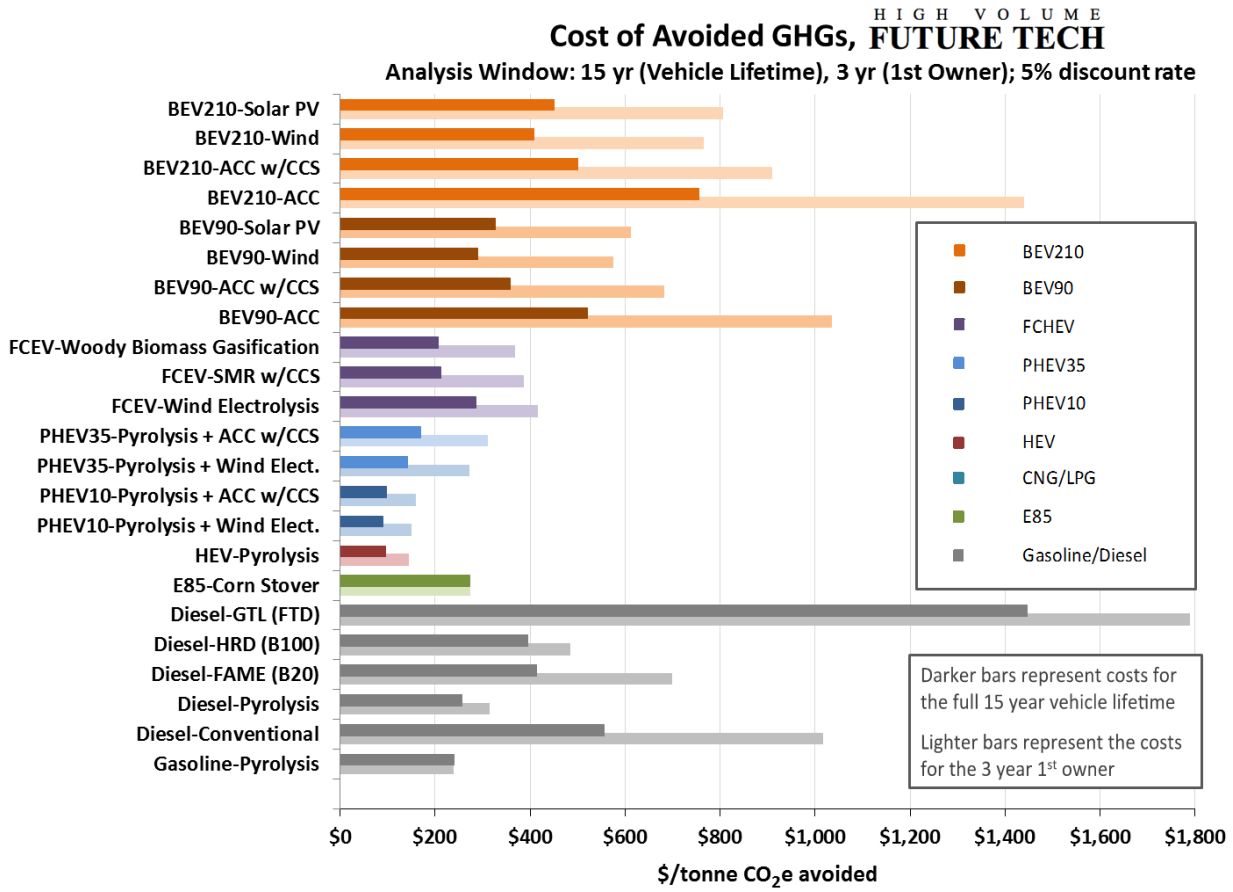

Figure ES-5. Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case (2013$), relative to the FUTURE TECHNOLOGY gasoline ICEV

The following observations are drawn from this report:

Emissions:

- Large GHG reductions for LDVs are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

Cost:

- High-volume production is critical to the viability of advanced technologies.
- Incremental costs of advanced technologies in FUTURE TECHNOLOGY, HIGH VOLUME cases are significantly reduced, reflecting estimated R&D outcomes.
- Low-carbon fuels can have significantly higher costs than conventional fuels.
- Vehicle cost is the major (60–90%) and fuel cost the minor (10–40%) component of LCD when projected at volume. Treatment of residual vehicle cost is an important consideration. Many alternative vehicles and/or fuels cost significantly more than conventional gasoline vehicles for the CURRENT TECHNOLOGY case, even when costs are projected for high-volume production.

Cost of carbon abatement:

- For the CURRENT TECHNOLOGY, HIGH VOLUME case, carbon abatement costs are generally on the order of $100s per tonne CO_2 to $1,000s per tonne CO_2 for alternative vehicle-fuel pathways compared to a conventional gasoline vehicle baseline.

- FUTURE TECHNOLOGY, HIGH VOLUME carbon abatement costs are generally expected to be in the range $100–$1,000/tonne CO_2.

Technology feasibility:

- Significant technical barriers still exist for the introduction of some alternative fuels. Further, market transition barriers – such as low-volume costs, fuel or make/model availability, and vehicle/fuel/infrastructure compatibility – may play a role as well.

Limitations:

- AEO 2015 data for prices of crude oil, gasoline, and diesel fuel used in the CURRENT TECHNOLOGY case differ from subject data reported for early 2016. Because these data are different and because they are among several factors considered in this analysis, the calculated CURRENT TECHNOLOGY LCD for gasoline and diesel and the CURRENT TECHNOLOGY cost of avoided GHG emissions for the other alternative pathways relative to gasoline would be different if 2016 prices were used. One of the consequences of using AEO 2015 data for the CURRENT TECHNOLOGY cases is that the prices of crude oil, gasoline, and diesel fuel used in this report are 40–50% higher than actual market prices for those products in the first quarter of 2016 (the time this report was written). This report examines current fuel costs in greater detail in Section 9.4 and Appendix F.
- This study evaluated GHG emissions and cost of individual pathways and assumed common vehicle platforms for comparison. The cost estimates in this study are subject to uncertainties due to their projection at both high- and low-volume production for the CURRENT TECHNOLOGY case and their dependence also on technology advancement for the FUTURE TECHNOLOGY case. Furthermore, market scenario analysis should build on this pathway analysis to explore the realistic potential of the mix of different pathways to achieve GHG emission targets in different regions.
- Key GHG emission parameters influencing the results of various pathways are subject to different degrees of uncertainty. For example, methane emissions of the CURRENT TECHNOLOGY natural gas pathway vary greatly between the various studies. Land use change attributed to large-volume biofuel production is another example of uncertainty and varies greatly between studies.
- Factors other than cost of avoided GHG emissions, such as air quality, vehicle functionality (range, refueling time and infrastructure availability, packaging), and fuel production scalability, are important but not captured in this study.

1 INTRODUCTION

The intent of this study is to provide a comprehensive lifecycle analysis (LCA), also known as a cradle-to-grave (C2G) analysis, of the projected costs and greenhouse gas (GHG) emissions of a variety of vehicle-fuel pathways. A thorough understanding of the sustainability merits of various fuel and vehicle technologies helps inform policy-making and product development plans. The evaluation of various vehicle-fuel technology combinations with respect to a given set of sustainability metrics requires a holistic approach, which can be achieved via LCA/C2G analysis of these vehicle-fuel systems.

1.1 CLIMATE AND POLICY CONTEXT

Energy access and security, climate change, atmospheric emissions, and water use are important long-term challenges for industry and governments. The U.S. transportation sector consumed 27.0 quadrillion Btu of primary energy sources in 2014, representing 27.5% of the total national energy consumption (EIA 2016a, Table 2.1). In 2014, petroleum supplied 91.6% of U.S. transportation energy consumption and 33.9% of the U.S. petroleum consumption was imported (EIA 2016a, Tables 2.5 and 3.3). The corresponding GHG emissions attributed to the transportation sector were 1,810 million metric tons (tonnes) of CO_2-equivalent (CO_2e), representing 26.3% of the total national GHG emissions (EPA 2016a, Table 2-10).

Anthropogenic climate change is largely attributed to increasing levels of GHGs in the Earth's atmosphere resulting from human activities (IPCC 2013). The largest contributor of radiative forcing[1] is the release of CO_2 during fossil fuel combustion (IPCC 2013). Light-duty vehicles (LDVs), the focus of this study, were responsible for approximately 60% of U.S. transportation sector GHG emissions in 2013 (EPA 2015a). The U.S. Department of Energy (DOE) has supported substantial research and development (R&D) of vehicle and fuel technologies to improve energy efficiency and reduce GHG emissions in the transportation sector. Advanced vehicle technologies include more efficient spark-ignition (SI) 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). Advanced fuel technologies include advanced biofuels, renewable electricity, and hydrogen.

The Energy Policy Act of 2005 was expanded and extended by the Energy Independence and Security Act of 2007 (EISA) to establish a Renewable Fuel Standard (RFS) with volume requirements for several categories of renewable fuels (GPO 2007). The RFS requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels. Established by the U.S. Environmental Protection Agency (EPA), the RFS program requires renewable fuels to be blended into transportation fuels in rising amounts each year, increasing to 36 billion gal by 2022. Each renewable fuel category in the RFS program must emit lower levels of GHGs relative to the petroleum fuel it replaces (EPA 2010a). More recently, the Obama Administration released its Climate Action Plan in June 2013 to cut carbon emissions in the United States, prepare the country for the impacts of climate change, and lead international efforts to address global climate change (White House 2013a). The Climate Action Plan targets the acceleration of cost-competitive advanced biofuels development and the deployment of cleaner fuels, including batteries and fuel cell technologies, to reduce GHG emissions from the transportation sector.

California's Low Carbon Fuel Standard (LCFS) requires fuel producers and importers who sell motor gasoline or diesel fuel in California to reduce their carbon intensity (measured in grams of CO_2e emissions per megajoule on a lifecycle basis) by an average of 10% from 2010 levels by 2020 (CARB

[1] Radiative forcing is the change in the balance of energy absorbed by the planet from sunlight and the energy radiated back into space from Earth due to some imposed perturbation (Myhre et al. 2013).

2015). The sought GHG emissions reduction can be achieved through more efficient refining and upstream operations as well as the mixing and increased sale of alternative low-carbon fuels. In the European Union (EU), the Renewable Energy Directive (RED) requires 10% of transportation energy consumption to be produced from renewable sources by 2020 (EC 2009a). The production of energy from renewable sources must achieve a minimum 35% reduction in life-cycle GHG emissions against conventional, petroleum-derived baseline fuels, with the threshold being elevated to 50% in 2018 (EC 2009b).

Further, the United States submitted an Intended Nationally Determined Contribution (INDC) to the United Nations indicating an intention to achieve an economy-wide target of reducing its GHG emissions by 26–28% below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%. The contribution of the transportation sector to meet these targets largely relies on fuel economy standards (USA 2015).

In 2010, the federal Corporate Average Fuel Economy (CAFE) requirement was set by EPA and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) at 34.1 miles per gallon gasoline equivalent (mpgge) for new U.S. fleet-wide car and truck sales by 2016 (GPO 2010). Subsequently, the CAFE standard was raised to 54.5 mpgge for model-year 2025. Achieving these new standards requires more efficient powertrains, as well as improved aerodynamics, lower rolling resistance, and reduced vehicle weight.

1.2 Previous LCA and C2G Work

The focus for LCAs of energy use and GHG emissions from LDVs in the United States has been vehicle fuel from extraction to consumption (also called the transportation fuel cycle). Such LCAs are also termed well-to-wheels (WTW) analyses, which can be further broken down into well-to-tank (WTT) and tank-to-wheels (TTW) stages. The WTT stage includes fuel production from the primary source of energy (feedstock) to its delivery to the vehicle's energy storage system (fuel tank, battery, etc.). The TTW stage includes fuel consumption during the operation phase of the vehicle. The results from WTT and TTW analyses are summed to give the WTW GHG emissions and energy use associated with each vehicle-fuel technology combination.

WTW analyses of conventional petroleum-powered ICEVs show that approximately 80% of the WTW GHG emissions and energy use are associated with the combustion of the fuel during vehicle operation (Elgowainy et al. 2014). In advanced vehicle technologies, the amount of fuel used by the vehicle is decreased while the energy used to produce the vehicle is usually increased. Thus, for advanced vehicle technologies, it is important to also consider emissions and energy use associated with the vehicle manufacturing cycle. Combining the vehicle and fuel cycle produces a C2G assessment that encompasses resource extraction (cradle), transformation of resources into fuels and vehicles, and fuel use in vehicle operation and vehicle end-of-life (EOL) scrappage and recycling (grave).

In 2014, the DOE published a C2G analysis that comprised two GHG emissions bookend pathways for various vehicle-fuel systems (Joseck and Ward 2014). The high GHG bookend pathway represented currently available fuel and vehicle technologies, such as gasoline-ICEVs, E85[2] for use in ICEVs, compressed natural gas (CNG) use in ICEVs, diesel ICEVs, gasoline HEVs, gasoline PHEVs, BEVs, and hydrogen (H_2) FCEVs. The low GHG bookend pathway represented fuels and vehicles in a hypothetical low-carbon world. The C2G results were produced with Argonne National Laboratory's Greenhouse gas, Regulated Emissions, and Energy use in Transportation (GREET™) model with inputs that were vetted

[2] E85 is a term that refers to high-level ethanol-gasoline blends containing 51%–83% ethanol by volume, depending on geography and season (AFDC 2015). This study assumes 83% ethanol blend in E85.

by experts from other national laboratories and from the energy and auto industries. This study includes those vehicle pathways, as well as an analysis of a liquefied petroleum gas (LPG) vehicle-fuel pathway. This study also expands upon the previous DOE C2G work and updates some of its assumptions (Joseck and Ward 2014).

1.3 OVERVIEW OF THE PRESENT C2G STUDY

This C2G study assesses more realistic future vehicle-fuel pathways than the previous hypothetical low-carbon bookend that could be available in the 2025–2030 timeframe. In addition to assessing GHG emissions and petroleum energy use, this study includes cost analyses of the pathways as well as estimates the technology readiness levels (TRLs) of key fuel and vehicle technologies along the pathways.

This C2G study focuses on the LDV market, particularly the midsize vehicle segment. The study evaluates a variety of conventional and alternative vehicle technologies as well as conventional and alternative vehicle fuels. In evaluating the vehicle-fuel combinations, this study considers both a "CURRENT TECHNOLOGY" case (nominally 2015) and a "FUTURE TECHNOLOGY" lower-carbon case (nominally 2025–2030).[3] Further, the study takes a "pathway" approach rather than a "scenario" approach. A pathway is defined as a distinct, technically feasible, route or sequence of processes starting with one or more feedstocks and ending with an intermediate or a final product. A pathway is not necessarily constrained by practical feedstock, economic, policy, and market considerations. This is in contrast with the definition of a scenario as a postulated vehicle-fuel production pathway or a mix of pathways that factor in real or hypothetical/perceived feedstock, economic, policy, and market considerations. This study focuses strictly on possible vehicle-fuel combination pathways (i.e., no scenario analysis was conducted in this study).

The fuel pathways considered in this study are shown in Table 1. We note that the selected fuel pathways are constrained to those deemed to be nationally scalable in the future. Additional concerns, such as consumer choice, regional variability, and infrastructure availability for FCEV and BEV, were not directly accounted for. Unless otherwise specified, all cases assume large scale for both fuel and vehicle technologies (i.e., high production volume is assumed unless explicitly specified). The electricity mix used in stationary processes in FUTURE TECHNOLOGY pathways (unless otherwise specified) comes from the 2030 U.S. grid generation mix projected by the U.S. Energy Information Administration (EIA) in the Annual Energy Outlook (AEO) 2015 (EIA 2015a).

[3] Throughout this report, the cases studied will be denoted in a SMALL CAPS typeface for consistency and clarity. Both the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases have been examined and will be specified when there is any difference between the two cases. The FUTURE TECHNOLOGY case is always examined at high-volume production of vehicles and fuels, as defined in Section 2, and will be explicitly listed as FUTURE TECHNOLOGY, HIGH VOLUME when compared with CURRENT TECHNOLOGY cases at varying production scales.

Table 1. Fuel production pathways considered in this C2G analysis

Fuel	CURRENT TECHNOLOGY Case	FUTURE TECHNOLOGY Case
Gasoline (E10)	U.S. average crude mix (blended with 10% corn ethanol)	Pyrolysis of forest residue (no ethanol blending)
Diesel	U.S. average crude mix	Pyrolysis of forest residue
		Hydroprocessed renewable diesel (HRD) from soybeans
		20% fatty acid methyl ester (FAME) drop-in bio-based diesel (B20) from soybeans[a]
		Gas-to-liquid Fischer-Tropsch diesel (GTL FTD)
CNG	U.S. average of conventional and shale gas mix	—
LPG	75% from U.S. conventional and shale gas mix and 25% from U.S. average crude mix	—
Ethanol (E85)	85% Corn ethanol (blended with 15% petroleum gasoline blendstock)	85% cellulosic from corn stover (blended with 15% petroleum gasoline blendstock)
Hydrogen	Centralized production from steam methane reforming (SMR)	Electrolysis from wind
		Biomass (poplar) gasification
		Natural gas SMR with carbon capture and storage (CCS)
Electricity	EIA-AEO U.S. average electricity generation mix in 2014	Natural gas (NG) advanced combined cycle (ACC)
		Natural gas ACC with CCS
		Wind
		Solar photovoltaic (PV)

[a] American Society for Testing and Materials (ASTM) specifications for conventional diesel fuel (ASTM D975) allows for biodiesel concentrations of up to 5% (B5) to be called diesel fuel (ASTM 2010). B20 (20% biodiesel, 80% petroleum diesel by volume) is a biodiesel blend available in the United States that represents the maximum allowable concentration of biodiesel in ASTM D7467. FAME is also known as biodiesel.

The vehicle technologies matched with the Table 1 fuel pathways are shown in Table 2. We note that each vehicle is presumed to be optimized for the fuel on which it operates. The PHEV10, PHEV35, BEV90, and BEV210 technologies are defined to have 10, 35, 90, and 210 mi of range, respectively, from a single full charge in real-world driving. PHEV10 was modeled as a power-split powertrain, while PHEV35 was modeled as an extended-range electric vehicle (EREV) (Moawad et al. 2016). The EREV propulsion system includes a fully capable electric drive unit that uses battery energy to satisfy vehicle torque and speed demands under all circumstances. When energy remains in the battery (i.e., when the vehicle is in “charge-depleting” [CD] mode), assistance from the internal combustion engine (ICE) is not required. Once battery energy is depleted, the vehicle switches to a “charge-sustaining” (CS) mode. In this mode, net energy consumed (engine output less electric regeneration from braking) is supplied by the onboard internal combustion fuel (e.g., gasoline). Torque applied to the wheels in CS mode may be fully supplied through the electric drive unit, or it may be supplied partially through the electric drive unit and partially through a mechanical connection from the engine output.

Table 2. Vehicle-fuel combinations considered in this C2G analysis

Vehicle Technology	Gasoline[a]	Diesel	CNG	LPG	E85[b]	H_2	Electricity
ICEV	X	X	X	X	X	–	–
HEV	X	–	–	–	–	–	–
H_2 FCEV	–	–	–	–	–	X	–
BEV90[c]	–	–	–	–	–	–	X
BEV210[d]	–	–	–	–	–	–	X
PHEV10 (power-split)[e]	75%[g]	–	–	–	–	–	25%[g]
PHEV35 (EREV)[f]	42%[g]	–	–	–	–	–	58%[g]

[a] Gasoline (E10) assumed to contain 10% corn ethanol by volume.

[b] Blend of ethanol fuel grade with gasoline as explained in footnote 2.

[c] BEV90 has 90 mi "on-road" driving range.

[d] BEV210 has 210 mi "on-road" driving range.

[e] PHEV10 has 10 mi "on-road" electric range and is modeled as a power-split PHEV.

[f] PHEV35 has 35 mi "on-road" electric range and is modeled as an EREV.

[g] The fraction of total miles driven on fuel or electricity is assumed per SAE (2010). The exact fraction for the nominal PHEV35 depends on its on-road range, as described in Section 3.2.

1.4 Report Organization

The remainder of this report is organized in eleven sections (2–12) and seven appendices (A–G). Section 2 provides an overview of the methodology for modeling fuel pathways and vehicle technologies. Section 3 describes the selected vehicle technologies and the TRL for each vehicle-fuel pathway. Section 4 describes the selected fuel pathways and the assumptions and data sources for calculating GHG emissions of these pathways in GREET. Section 5 provides cost assumptions for various fuels and the relevant data sources. Section 6 describes the Autonomie modeling approach and assumptions for each vehicle's fuel economy, cost, and weight/material composition. Section 7 explains the lifecycle stages of vehicle manufacturing and relevant data sources in GREET. Section 8 provides the C2G GHG emissions results. Section 9 provides the levelized cost of driving (LCD) results. Section 10 provides the projected costs of avoided GHG emissions for various vehicle-fuel systems. Section 11 identifies limitations in the current studies for consideration in future studies. Section 12 provides brief conclusions about this work.

Appendix A provides a simplified description of the fuel pathways and the key stages and provides the estimates for the key parameters that impact GHG emission results significantly in each pathway. Appendix B compares vehicles modeled in this report with vehicle sales data. Appendix C provides more detailed GHG emissions results. Appendix D analyzes the sensitivity of GHG emission and cost results to key parameters in selected vehicle-fuel pathways. Appendix E provides example calculations of the LCD to clarify how these costs were developed. Appendix F examines different fuel price assumptions to examine the sensitivity to fuel costs. Finally, Appendix G compiles all the references used in this study by aggregating the references provided at the end of each section.

1.5 References for Section 1

AFDC (Alternative Fuels Data Center), 2015. *E85*. http://www.afdc.energy.gov/fuels/ethanol_e85.html

ASTM (American Society of Testing and Materials) International, 2010. *ASTM D5975-96, Standard Test Method for Determining the Stability of Compost by Measuring Oxygen Consumption*. ASTM International, West Conshohocken, PA. http://www.astm.org/Standards/D5975.htm

CARB (California Air Resources Board), 2015. Low Carbon Fuel Standard Regulation. http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

Elgowainy, A., J. Han, H. Cai, M. Wang, G.S. Forman, and V.B. DiVita, 2014. "Energy Efficiency and Greenhouse Gas Emissions Intensity of Petroleum Products at US Refineries," *Environmental Science and Technology*, doi: 10.1021/es5010347. http://pubs.acs.org/doi/abs/10.1021/es5010347

EC (European Community), 2009a. *Directive 2009/28/EC of the European Parliament and of the Council, on the Promotion of the Use of Energy from Renewable Sources*. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028

EC, 2009b. *Directive 2009/30/EC of the European Parliament and of the Council, on the Specification of Petrol, Diesel and Gas-oil and Introducing a Mechanism to Monitor and Reduce Greenhouse Gas Emissions*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0030

EIA (U.S. Energy Information Administration), 2015a. *Annual Energy Outlook 2015 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

EIA, 2016a. *Monthly Energy Review*. http://www.eia.gov/totalenergy/data/monthly/

EPA (U.S. Environmental Protection Agency), 2010a. "Regulation of Fuels and Fuel Additives: 2011 Renewable Fuel Standards." *Federal Register*, December 9; Vol. 75 (No. 236): 76790–76830. https://www.federalregister.gov/articles/2010/12/09/2010-30296/regulation-of-fuels-and-fuel-additives-2011-renewable-fuel-standards

EPA, 2015a. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990–2013*. EPA-420-F-15-032. https://www.epa.gov/sites/production/files/2016-02/documents/420f15032.pdf

EPA, 2016a. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013*. EPA 430-R-16-002. https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf

GPO (Government Printing Office), 2007. *Energy Independence and Security Act*. https://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf

GPO, 2010. *Environmental Protection Agency and Department of Transportation: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule*. https://www.gpo.gov/fdsys/pkg/FR-2010-05-07/pdf/2010-8159.pdf

IPCC (Intergovernmental Panel on Climate Change), 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY. doi:10.1017/CBO9781107415324 http://dx.doi.org/10.1017/CBO9781107415324

Joseck, F., and J. Ward, 2014. *Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways*. https://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

Moawad, A., N. Kim, N. Shidore, and A. Rousseau, A., 2016. *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies.* Report ANL/ESD-15/28. Argonne National Laboratory, Argonne, IL. http://www.autonomie.net/publications/fuel_economy_report.html

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013. "Anthropogenic and Natural Radiative Forcing." In: *Climate Change 2013: The Physical Science Basis.*

Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf

SAE (Society for Automotive Engineers) International, 2010. *Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data*. http://standards.sae.org/j2841_201009/

USA, 2015. *Intended Nationally Determined Contribution (INDC) Submitted to the United Nations*. March 31. http://www4.unfccc.int/submissions/INDC/Published%20Documents/United%20States%20of%20America/1/U.S.%20Cover%20Note%20INDC%20and%20Accompanying%20Information.pdf

White House, Executive Office of the President, 2013a. *The President's Climate Action Plan*. https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf

2 OVERVIEW OF METHODOLOGY

The primary intent of this study is to gain an understanding of energy use, GHG emissions, technology readiness, and costs for each vehicle-fuel combination and allow for comparisons across those combinations. To enable comparisons over a wide variety of vehicle-fuel pathways, a consistent set of parameters and common analysis framework was used in the evaluation. This section provides an overview of the data, assumptions, and analysis methodology used in this C2G study.

2.1 STUDY SCOPE, DEFINITIONS AND MAJOR ASSUMPTIONS

To narrow the scope of the evaluation, this C2G analysis focuses on the midsize class of LDVs (such as the Chevrolet Malibu, Dodge Dart, and Ford Fusion). Results for other vehicle classes will differ from the results reported from this study, but the evaluation of the midsize class should provide a general understanding and direction of the lifecycle results for other LDV classes. Fuel and vehicle options were limited to opportunities that could meet the demand of approximately 10% of the fleet.

Tables 1 and 2 outline the vehicle and fuel technologies considered in this analysis, which include ICEVs, HEVs, PHEVs, FCEVs, and BEVs operating on a variety of fuel types.

The C2G assessment consists of two major elements: an evaluation of lifecycle GHG emissions and energy use for each pathway and an assessment of the costs associated with each pathway. The GHG and vehicle and fuel cost assessments are in turn used to model the cost of avoided GHG emissions. To support these evaluations, this analysis relies on an assessment of conventional and alternative vehicle platforms, including an evaluation of vehicle platform itself, the cost of the vehicle, and the fuel economy of the vehicle. This analysis also relies on evaluations and cost modeling of fuel technologies. A technology readiness assessment (discussed in Section 3.3) rounds out the analysis to provide a more comprehensive picture of how the pathways fare against each other.

In this analysis, "cost" is defined as policy-neutral final transaction cost. In this context, costs are the final cost/price to the consumer, excluding tax on the final product (e.g., fuel sales tax) and/or credits (e.g., vehicle subsidies). This framework intentionally excludes policy interventions to address technology or market challenges and opportunities. Throughout this report, costs are reported in 2013$ using the U.S. Bureau of Economic Analysis Implicit Price Deflator for Gross Domestic Product to convert costs to consistent 2013 dollars (BEA 2015, Table 1.1.9).

Cost estimates for both vehicles and fuels are based on high-volume production ("at/above optimal scale"), which is intentionally not standardized across vehicle-fuel pathways, since scale is recognized as inherently a function of the technology/production pathway. Some examples of fuel and vehicle technology scale/volume assumptions used in the study are shown in Table 3. A current technology case, CURRENT TECHNOLOGY, HIGH VOLUME, was modeled to represent vehicle model year (MY) 2015 and to characterize fuel production technologies available in 2015, with costs projected at high volume. In some instances, a sensitivity low-volume case, CURRENT TECHNOLOGY, LOW VOLUME, was evaluated to calculate cost of new vehicles at low volume (e.g., between 10,000 and 100,000 units of FCEVs) and low-volume fuel production/distribution (e.g., hydrogen). The FUTURE TECHNOLOGY, HIGH VOLUME case represents MY2025–2030 vehicles and fuels projected at high volume.

Though the study does consider low-volume costs in some instances, the primary evaluation is of vehicles and fuels at high production volume, and the costs of transitioning to high-volume production are not considered.

Table 3. Vehicle scale assumptions by technology

Pathway Element	Parameter	Volume/Scale Assumption
Vehicle	Engines	200,000+ vehicles/year
	Energy storage	100,000+ batteries/year
	Fuel cell stack	500,000+ fuel cell vehicles/year
Hydrogen fuel	Production	Electrolysis at 50,000 kg/day; SMR at 384,000 kg/day
	Distribution	100 tonnes/day
Bio-derived fuel	Production	2,000 dry tonnes of feedstock per day to yield 6,000–9,000 bbl/day of ethanol or ~4,000 bbl/day of gasoline/diesel by pyrolysis

2.2 Approach of Greenhouse Gas Emissions and Energy Use LCA

In assessing lifecycle emissions, this study considers both emissions associated with the fuel cycle and emissions associated with the vehicle cycle. The C2G GHG emissions assessment was carried out by expanding and modifying the GREET™ model suite with inputs from industrial experts[4]. Figure 1 shows the main lifecycle 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 recovery (or growth in the case of biofuels) of the primary feedstock; transportation of the feedstock; production of the fuel from the feedstock; and 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, and the EOL decommissioning and recycling of vehicle components.

GREET1 contains over 100 vehicle-fuel system combinations. Fuel types include gasoline, diesel, biofuels, hydrogen, NG-based fuels, and electricity. See Figure 1 for a GREET1 fuel production pathway example. Vehicle technologies in GREET1 include ICEVs, HEVs, PHEVs, BEVs, and FCEVs.

GREET2 calculates vehicle-cycle energy use and emissions for various vehicle types and material compositions. The vehicle cycle for each vehicle type and material composition includes the following processes: (1) raw material recovery and extraction, (2) material processing and fabrication, (3) vehicle component production and vehicle assembly, and (4) vehicle disposal and recycling. Currently, the model does not include energy use and emissions from transportation of raw and processed materials for each process step. However, future versions of the model will likely address this issue because the location of each process step is important in determining urban air quality impacts. Material production can take place outside of the United States.

[4] This analysis uses the GREET 2014 release from Argonne National Laboratory (Argonne 2014)

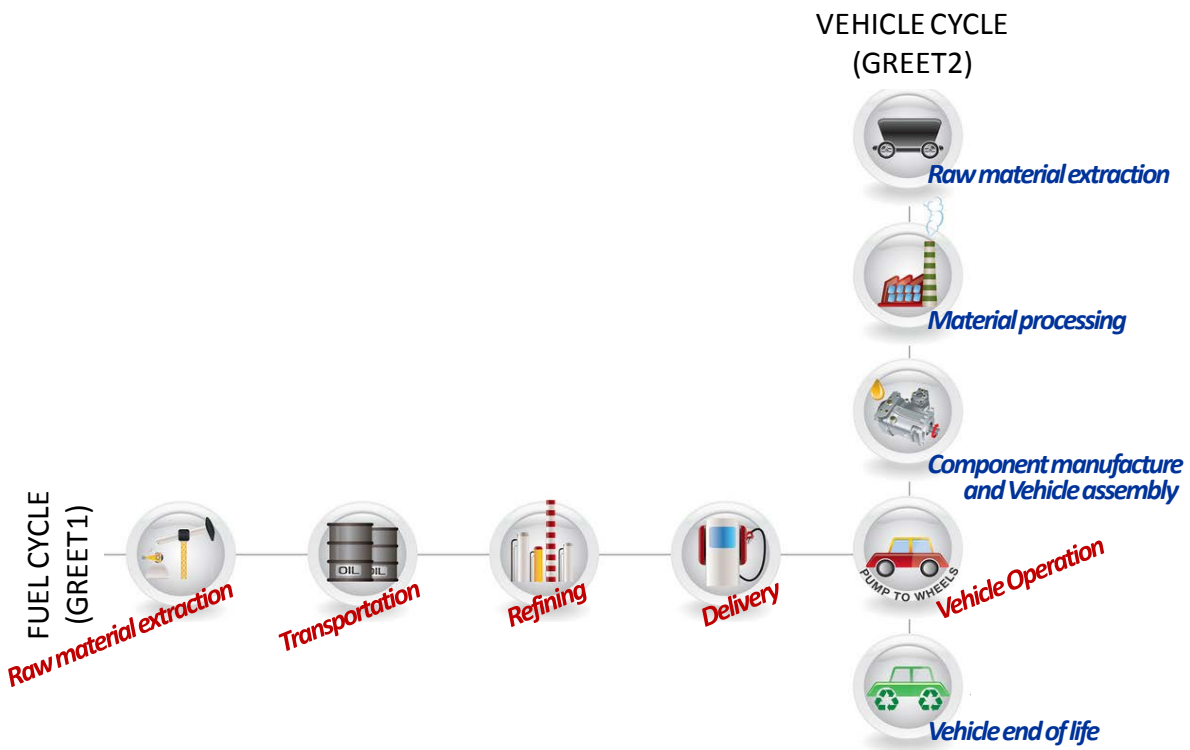

Figure 1. Combined fuel cycle and vehicle cycle activities included in C2G analysis

The first step of the vehicle-cycle analysis is to estimate vehicle component weight. This estimate takes into account the weight of the major components of a vehicle, such as the body (including body-in-white[5], body interior, body exterior, and glass), chassis, batteries, fluids, powertrain (e.g., an SI engine or a fuel cell stack and auxiliaries), and transmission or gearbox. Depending on the vehicle type, the component weight could include the weight of a motor, controller, and generator. Second, for each major vehicle component, the vehicle-cycle model considers its material composition (i.e., breakdowns of total component weight into steel, aluminum, iron, plastic, rubber, and any other materials).

For components that are subject to replacement during a vehicle's lifetime (e.g., batteries, tires, and various vehicle fluids), the model develops replacement schedules. For disposal and recycling, the model takes into account the energy required and emissions generated during recycling of scrap materials back into original materials for reuse. Finally, the estimates of energy used during the processes from raw material recovery to vehicle assembly (e.g., mining taconite and processing it into sheet steel to be stamped) are used for vehicle-cycle simulations.

2.3 Vehicle Modeling Approach

Modeling of the various vehicle technologies evaluated in this study was conducted using publicly available data and models. Vehicle fuel economies and component sizes were estimated by Argonne National Laboratory's vehicle simulation tool, Autonomie, using a consistent set of vehicle performance criteria across fuel-vehicle combinations. Each vehicle is presumed to be optimized for the fuel on which

[5] Body-in-white refers to the welded assembly of a car body's structural sheet metal components.

it operates. Inputs to Autonomie were based on vehicle manufacturer's information and assumptions made by the authors.

This study spanned the full portfolio of LDVs, including conventional internal combustion, hybrid electric, plug-in hybrid electric, fully electric, and fuel cells, and the fuels that power them (petroleum, natural gas, LPG, ethanol, hydrogen, and electricity). To ensure that analysis results reflect only the differences in fuel pathways and vehicle operation, rather than any potential confounding factors, e.g., aesthetic differences in vehicle design, vehicles are assumed to be identical in capability and performance. Overall, vehicles were modeled using a common vehicle "glider" coupled with modeling of specific components for each vehicle platform (transmission, engine/motor, energy storage/fuel tank, emission controls, etc.).

The vehicle attribute that characterizes energy consumption and, therefore, all other metrics of interest, is vehicle efficiency, expressed in this study as fuel economy. For the set of vehicles examined, fuel economies are expressed in gge terms as a percentage of the baseline vehicle. The baseline vehicle (SI ICEV) is a typical midsize sedan with an assumed fuel economy of 26.4 mpg for the CURRENT TECHNOLOGY case.[6] Fuel economy assumptions were based on scenario results from Autonomie, with all vehicle platforms evaluated using standard EPA drive cycles. Autonomie modeling reflected vehicle performance improvements in line with DOE Vehicle Technologies Office and Fuel Cell Technology Office targets for advanced vehicles. A range of future vehicle cost estimates were developed based on a range of technology progress (more optimistic and less optimistic), resulting in a low to high cost range. The base vehicle platform costs were based on an average of the cost range endpoints.

2.4 FUEL MODELING APPROACH

Fuels evaluated in this study include conventional gasoline and diesel; NG-based fuels; biofuels, including ethanol, pyrolysis fuels, and various biodiesel fuels; hydrogen for fuel cell vehicles; and electricity produced from various pathways for electric and plug-in hybrid vehicles. In particular, feedstocks and fuel production pathways include:

- Corn stover for E85
- Fast pyrolysis forest residue and corn stover for renewable gasoline and diesel
- GTL for diesel with and without CCS
- CNG
- LPG
- Soybeans (soy oil to renewable diesel and FAME)
- Electrolysis—NG reforming with CCS and woody biomass gasification—for hydrogen
- Electricity for PHEVs and BEVs (as described below).

A complete list of fuel pathways considered is presented in Table 1. Overall, fuel pathways selected are considered to be scalable and capable of meeting 10% of fleet demand.

Similar to vehicle modeling, modeling of the fuels investigated in this study was based on publicly available data and models. For transportation fuels currently at large-scale production levels—gasoline, diesel, CNG, LPG, and corn-based ethanol (E85)—current and future fuel cost estimates come from the EIA AEO 2015 (EIA 2015a). The CURRENT TECHNOLOGY case assumes the AEO 2015 average electricity grid mix for all pathways. For the FUTURE TECHNOLOGY case, production of electricity for electric vehicles and hydrogen for FCEVs is based on EIA's 2015 estimates of the levelized cost of electricity from new generation resources. This includes estimates for solar electricity, wind electricity,

[6] Combined EPA two-cycle (adjusted) fuel economy.

and electricity from ACC generation. Electricity for the other FUTURE TECHNOLOGY case pathways is based on the AEO 2015 projected average grid mix for 2030.

For the remaining fuels, this study based its cost assessment on publicly available data and models. The hydrogen fuel pathways and several of the bio-derived fuel pathways were evaluated using a variety of techno-economic analysis (TEA) models developed by DOE and its national laboratories. These TEA models use a discounted cash flow, rate-of-return analysis methodology to return a minimum selling price of producing, delivering, and dispensing hydrogen and liquid biofuels, accounting for capital, feedstock, and operating and maintenance costs as a function of feedstock composition, operation conditions, and process conversion efficiency. In most instances, rather than relying on published costs for these fuels, we used the publicly available TEA models to generate fuel costs using a standard set of assumptions chosen specifically for this study. This helped ensure that fuel evaluations were consistent across fuel pathways. Common parameters for TEA modeling included internal rate of return (IRR), finance rate, (facility) depreciation rate, overall (federal and state) tax rate, and feedstock price inputs. Finally, some of the biofuels were evaluated using external models and reports.

Specific details on the sources of data and modeling for each of the fuel pathways are found in Sections 4 and 5. Table 4 provides an overview of the data and models used in this study.

Table 4. Overview of vehicle and fuel cost models and data sources

<table>
<tr><th rowspan="2">Technology</th><th rowspan="2">Vehicle Data Source</th><th colspan="7">Fuel Data Source</th></tr>
<tr><th>Gasoline</th><th>Diesel</th><th>CNG</th><th>LPG</th><th>E85</th><th>H_2</th><th>Electricity</th></tr>
<tr><td>ICEV</td><td rowspan="5">DOE vehicle costing analysis (Autonomie)</td><td colspan="4" rowspan="2">EIA AEO (and TEA models for FUTURE TECHNOLOGY pathways)</td><td rowspan="2">TEA models</td><td rowspan="4"></td><td rowspan="2"></td></tr>
<tr><td>HEV</td></tr>
<tr><td>PHEV</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="4">EIA AEO</td></tr>
<tr><td>BEV</td></tr>
<tr><td>FCEV</td><td>H2A, HDSAM models</td></tr>
</table>

2.5 REFERENCES FOR SECTION 2

Argonne National Laboratory, Systems Assessment Group, 2014. *GREET Model, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. https://greet.es.anl.gov/index.php

BEA (Bureau of Economic Analysis), U.S. Department of Commerce, 2015. *National Income and Produce Account Tables*. http://www.bea.gov/iTable/iTableHtml.cfm?reqid=9&step=3&isuri=1&903=13

EIA (U.S. Energy Information Administration), 2015a. *Annual Energy Outlook 2015 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

DOE, Hydrogen and Fuel Cells Program, 2015a. *Production Case Studies*. https://www.hydrogen.energy.gov/h2a_prod_studies.html

DOE, Hydrogen and Fuel Cells Program, 2015b. *DOE H2A Delivery Analysis*. https://www.hydrogen.energy.gov/h2a_delivery.html

DOE, Hydrogen and Fuel Cells Program, 2015c. *DOE H2A Production Analysis*. https://www.hydrogen.energy.gov/h2a_production.html

3 VEHICLE-FUEL PATHWAY SELECTION AND VEHICLE TECHNOLOGIES

3.1 VEHICLE-FUEL PATHWAYS

This C2G analysis spanned a full portfolio of LDVs—conventional ICEVs, HEVs, PHEVs, BEVs, and FCEVs—as well as the fuels that power them (petroleum, CNG, LPG, ethanol, hydrogen, and electricity). The primary intent of this study was to gain an understanding of energy use and emissions ranges for each vehicle-fuel combination and allow for comparisons across those combinations. In all cases, the vehicles were presumed to be optimized for the fuel on which they operate. Table 2 shows the 11 vehicle-fuel combinations that were analyzed.

To ensure that analysis results reflect only the differences in fuel pathways and vehicle operation, rather than confounding factors, vehicles are assumed to be identical in size, shape, and weight (except for changes to the powertrain) with identical capability and performance. A consistent set of parameters were chosen to allow a broad spectrum of vehicle-engine type and fuel options to be compared. The primary intent is to gain an understanding of energy use and emissions ranges for each vehicle-fuel combination and allow for comparisons across those combinations. A single vehicle classification (midsize) was analyzed to limit the scope of this effort. The baseline vehicle ("gasoline ICEV") is a typical midsize sedan operating on conventional gasoline (E10).

The fuel pathways considered in this study were limited to those that in the opinion of the authors could plausibly meet the demand of approximately 10% of the U.S. LDV fleet. The fuel pathways (Table 1) were chosen to span the range from today's mainstream offerings to relatively low-carbon fuel cases in the future. The generation of electric power from wind and solar was assumed to be zero-carbon. A detailed description of the vehicle technologies and fuel pathways used in this analysis is given in the following sections.

3.2 DESCRIPTION OF SELECTED VEHICLE TECHNOLOGIES

CURRENT TECHNOLOGY (MY2015) technologies are estimated based on recent state-of-the technology lab demonstration. FUTURE TECHNOLOGY (MY2025–2030) estimates consider a range of possible technology pathways and explicitly recognize uncertainty (low, medium, high) in technology progress, as discussed in Section 6. It is important to emphasize that Autonomie models generic vehicles employing particular technologies rather than specific makes and models. Variability in the market is not reflected, by design; this uniform approach allows us to compare across technologies without confounding effects. Further details on the methods and assumptions used in the Autonomie model to derive the generic vehicles are available in Moawad et al. (2016).

This analysis includes four types of plug-in vehicles: all-electric vehicles with ranges of 90 mi (BEV90) and 210 mi (BEV210), and plug-in hybrid electric vehicles with charge-depleting ranges of 10 mi (PHEV10) and 35 mi (PHEV35). These vehicles were taken from Moawad et al. (2016), where they were labeled BEV100, BEV300, PHEV10, and PHEV40, respectively. There is no universally accepted naming system for PHEVs, and this can often lead to confusion. Care needs to be taken in the interpretation of the battery and/or charge-depleting driving ranges indicated by the numbers following "BEV" and "PHEV." These values can refer to ranges measured on EPA CAFE drive cycles or estimated for real-world driving. Furthermore, they can refer to ranges measured at the vehicle beginning of life (BOL) or estimated at the EOL, after battery capacity has deteriorated. In this report, we have opted to refer to estimates of real-world ranges, which are most relevant to customers. By reflecting higher speed, more aggressive driving, and the use of accessories (e.g., air conditioning) not accounted for in the EPA

CAFE drive cycles, the real-world fuel economy achieved by modern vehicles is typically less than that measured in the EPA CAFE drive cycles. This gap generally increases with the efficiency of the vehicle (use of accessories such as air conditioning has a larger relative impact) and for highly efficient vehicles, such as electric vehicles, the real-world fuel economy, and hence driving range, can be 30% less than that measured using EPA CAFE drive cycles. Since the PHEV10 is a blended PHEV (i.e., the gasoline engine is used throughout the entire drive cycle), the actual driving range in the electric-only mode can vary significantly based on the control strategy, and simple conversion to reflect real-world driving is not appropriate.

To avoid complications with estimates of battery deterioration over the vehicle life and for consistency with the marketplace, where manufacturers will advertise higher (i.e., BOL) rather than lower (EOL) driving ranges, we have opted to quote BOL ranges. In the Autonomie report, BOL is used for the BEV300, but EOL is used for the BEV100 and PHEV40 (Moawad et al. 2016). As a result of using an EOL naming basis, the batteries for the BEV100 and PHEV40 in the Autonomie model are oversized by 30% for laboratory year 2010 and by 25% for laboratory year 2020, relative to the similar vehicle named on a BOL basis (Moawad et al. 2016). In the referenced report, the BEV300 is already named based on BOL, and therefore the battery for the BEV300 is not oversized. We have placed the plug-in vehicles in the Autonomie model on a consistent set of real-world BOL ranges, using an adjustment of 70% of the CAFE drive cycles to represent real-world ranges.

Example calculations to arrive at a consistent (BOL, real-world) naming convention for the vehicles in this report are shown in Table 5. The breakdown of total miles driven on gasoline and electricity for the PHEV35 was calculated using the fleet utility factor coefficients in SAE (2010). The calculated value was approximately 42% for gasoline and 58% for electricity and was assumed constant over the lifetime of the vehicle.

Table 5. Comparison of naming conventions in this report and the Autonomie study (Moawad et al. 2016)

Name in Moawad et al. (2016)	Conversion	Name in this Report
2010 PHEV40	40×1.3×0.7 = 36, rounded to 35	CURRENT TECHNOLOGY PHEV35
2010 BEV100	100×1.3×0.7 = 91, rounded to 90	CURRENT TECHNOLOGY BEV90
2010 BEV300	300×0.7 = 210	CURRENT TECHNOLOGY BEV210
2020 PHEV40	40×1.25×0.7 = 35	FUTURE TECHNOLOGY PHEV35
2020 BEV100	100×1.25×0.7 = 88, rounded to 90	FUTURE TECHNOLOGY BEV90
2020 BEV300	300×0.7 = 210	FUTURE TECHNOLOGY BEV210

Vehicle fuel economies and component sizes were estimated by Autonomie using a consistent set of vehicle performance criteria across vehicle-fuel combinations. Each vehicle is presumed to be optimized for the fuel on which it operates. Inputs to Autonomie were based on vehicle manufacturer's information and Argonne assumptions. Vehicles modeled in Autonomie met the following criteria: (1) vehicle acceleration from 0 to 60 mph in 9 sec (±0.1 sec), (2) gradeability of 6% at 65 mph at gross vehicle weight (GVW), (3) maximum vehicle speed ≥100 mph, and (4) at least 160,000 lifetime miles per vehicle, except for BEV90 at 110,000 miles due to its limited range (NHTSA 2006; Francfort et al. 2015).

Since all vehicle powertrains considered in this analysis are already commercially available, vehicle technology is not seen as a limiting factor for the overall technology readiness of any vehicle-fuel pathway considered; however, it should be noted that the relatively high incremental cost of electric-drive

technologies (PHEV10, PHEV35, BEV90, BEV210, and H_2 FCEV) still poses a market barrier in the near term.

3.3 TECHNOLOGY READINESS LEVELS (TRLS)

Technology readiness levels are used as a metric to define the current status of a technology to determine whether it is mature enough to be implemented effectively. More commonly, TRLs are used to compare the maturity of different types of technologies that serve similar purposes. DOE adopted the TRLs developed by the National Aeronautics and Space Administration (NASA) in the 1980s for guidance on the technological maturity of energy-related applications (DOE 2013a, 2014b). Figure 2 shows the nine readiness levels, which range from basic technology research (TRL 1) to commercialization (TRL 9).

In TRLs 1 and 2, basic technology research is still being done. TRL 1 is the lowest level of technology readiness, where basic principles are observed and reported, and TRL 2 involves the formulation of a technology concept or an application. Once this stage is reached, active research and deployment is initiated to prove feasibility in TRL 3, by developing critical function and/or proof of concept. TRLs 4 and 5 describe the subsequent technology development, with component and/or small-scale system validation in laboratory environments and application-relevant environments, respectively. TRL 6 extends these and represents an engineering-scale prototypical system validation in the relevant environment. This demonstration goes well beyond the scales tested before, representing a major incremental advance in the demonstrated readiness of the technology, and it can be considered the beginning of true engineering development of the technology as an operational system (DOE 2014b).

System commissioning occurs in TRLs 7 and 8. TRL 7 requires a prototype full-scale system, larger than the system tested in TRL 6. In TRL 8, the technology has been proven to work in its final form under expected conditions. TRL 9 represents the systems operation phase. Here, the actual system is operational over the full range of expected operating conditions.

TRLs are used in this study to contextualize the current status and technical feasibility of each of the pathways before delving into the environmental and techno-economic analysis. TRLs capture the fact that there are many considerations in addition to cost and emissions to bring a technology to market. We assessed the TRLs of each vehicle-fuel pathway to compare development status and understand barriers to commercialization. To provide a comprehensive picture of the technology barriers, each pathway was broken down into the following segments: vehicle, energy feedstock, fuel production, fuel distribution, fuel dispensing, fuel specifications, and consumer acceptance. Based on both non-technical barriers and numerical TRLs for each pathway, each segment of each pathway was categorized as having “no major barriers,” “some significant barriers,” or “considerable barriers,” as indicated in Table 6. It is important to note that TRLs do not address resource availability or geographical constraints. The table shows the results of this exercise: significant technical barriers still exist for the introduction of some alternative fuels. For some pathways, additional non-technical barriers, such as fuel availability and compatibility with existing delivery systems, may play a role too.

The numerical TRL for each pathway is the lowest TRL assigned in the value chain, signaling that the technology bottlenecks determine pathway readiness. Since all vehicle powertrains considered in this analysis are already commercially available in the market, vehicle technology was not a limiting factor for the overall technology readiness of any vehicle-fuel pathway considered; however, it should be noted that the relatively high incremental costs of electric-drive technologies (PHEV10, PHEV35, BEV90, BEV210, and FCEV) still pose a near-term market barrier.

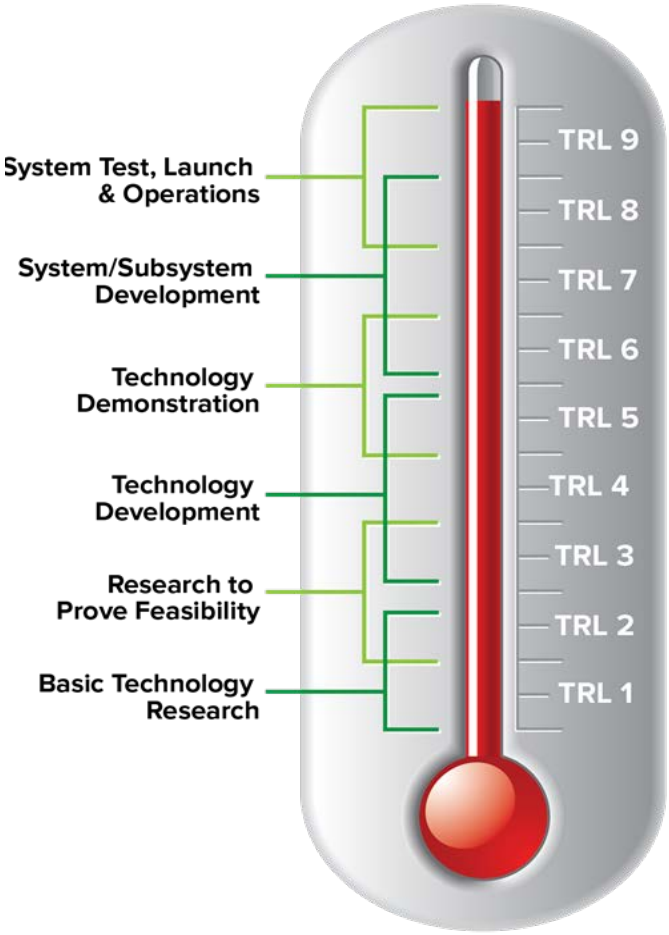

Figure 2. Technology readiness levels

Feedstock presents some significant barriers for biomass and renewable power-based pathways. In the case of biomass, the barriers are mainly due to limited availability (collection logistics and competing purposes), geographic restrictions, and high cost. In the case of wind and solar power, the resource is limited by its intermittency and geographical restrictions.

We determined that considerable production barriers exist only for pathways with CCS, since it has not been widely deployed, has geographic restrictions, faces an uncertain regulatory environment, is expensive in most cases, and lowers plant efficiency. The bio-derived pathways are not currently produced at scale, and they require an additional oxygen removal step (cost) and improvements in process performance (e.g., catalyst, cost). The TRLs for each bio-derived pathway in this report (Table 6) are sourced from literature: pyrolysis from forest residue has TRLs 6–7 (Lane 2015; Müller-Langer et al. 2014), GTL FTD has TRL 9 (Shuster et al. 2014), HRD and FAME from soybeans each have TRL 9 (Müller-Langer et al. 2014), fermentation of corn stover has TRL 8 (Globe 2010; DOE 2014a), and woody biomass gasification has TRL 7 (Müller-Langer et al. 2014).

The hydrogen distribution system presents challenges for the widespread deployment of FCEV technologies, given the absence of an existing pipeline distribution network and the limitations of delivering hydrogen by truck.

Table 6. Results of the TRL analysis[a]

Factor	Gasoline	Diesel					Ethanol	Pyrolysis-based Gasoline/Electricity (PHEV)				Electricity (BEV)				Hydrogen				
	Pyrolysis – forest residue	Pyrolysis – forest residue	GTL FTD w/o CCS	GTL FTD w/ CCS	HRD – soybeans	FAME – soybeans	Fermentation – corn stover	ACC w/o CCS	ACC w/ CCS	Wind	Solar	ACC w/o CCS	ACC w/ CCS	Wind	Solar	Electrolysis – Wind	Electrolysis – Solar	SMR w/o CCS	SMR w/ CCS	Woody biomass gasification
Vehicle																				
Feedstock																				
Production																				
Distribution																				
Dispensing																				
Fuel Spec																				
Consumer acceptance																				
TRL	6–7	6–7	9	7	9	9	8	6–7	6–7	6–7	6–7	9	7	9	9	8–9	8–9	8–9	7	7

[a] Green shading – no major barriers; yellow shading – some significant barriers; orange shading – major barriers.

Dispensing systems for innovative fuels and plug-in stations for electric vehicles face a number of challenges. For instance, very few manufacturers can provide high-pressure hoses for hydrogen dispensed at 700 bar; they are expensive and not currently manufactured at high volumes. Further, hydrogen dispensing technologies are still in the learning phase. Charging stations can have high installation costs and require substantial coordination among equipment vendors, installers, and host organizations to address construction, safety, and code requirements.

Fuel specification does not present barriers, except in the case of FAME from soybean, where some regulators and vehicle manufacturers restrict the volume that can be blended with diesel.

Consumer acceptance of FCEVs and BEVs may be slowed by refueling inconvenience (scarcity of hydrogen stations, limited range and long charging time with batteries); given the wide availability of gasoline and diesel stations, the burden to find an alternative fuel source is an important barrier to market penetration.

3.4 References for Section 3

DOE (U.S. Department of Energy), Office of Environmental Management, 2013a. *Technology Readiness Assessment (TRA) / Technology Maturation Plan (TMP) Process Implementation Guide*. http://energy.gov/em/downloads/technology-readiness-assessment-tratechnology-maturation-plan-tmp-process-guide

DOE, 2014a. *Abengoa*. http://www.energy.gov/eere/bioenergy/abengoa

DOE, 2014b. *Bioenergy Technologies Office Multi-Year Program Plan*. July. http://www.energy.gov/sites/prod/files/2014/07/f17/mypp_july_2014.pdf

Francfort, J., B. Bennett, R. Carlson, T. Garretson, L. Gourley, D. Karner, M. Kirkpatrick, P. McGuire, D. Scoffield, M. Shirk, S. Salisbury, S. Schey, J. Smart, S. White, and J. Wishart, 2015. *Plug-in Electric Vehicle and Infrastructure Analysis*. Report INL/EXT-15-35708, Idaho National Laboratory. http://avt.inel.gov/summaryreport.shtml

Globe Newswire, 2010. *Abengoa Bioenergy and Mid-Kansas Electric Reach Agreement Concerning First Commercial-Scale Hybrid Cellulosic Ethanol and Power Plant in U.S.* January 19. http://www.globenewswire.com/news-release/2010/01/19/412515/182207/en/Abengoa-Bioenergy-and-Mid-Kansas-Electric-Reach-Agreement-Concerning-First-Commercial-Scale-Hybrid-Cellulosic-Ethanol-and-Power-Plant-in-U-S.html

Lane, J., 2015. "The Pyromaniax, Class of 2015: The Top 10 Pyrolysis Projects in Renewable Fuels." *Biofuels Digest*, August 3. http://www.biofuelsdigest.com/bdigest/2015/08/03/the-pyromaniax-class-of-2015-the-top-10-pyrolysis-projects-in-renewable-fuels/

Moawad, A., N. Kim, N. Shidore, and A. Rousseau, 2016. *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies.* Report ANL/ESD-15/28, Argonne National Laboratory, Argonne, IL. http://www.autonomie.net/publications/fuel_economy_report.html

Müller-Langer, F., S. Majer, and S. O'Keeffe, 2014. "Benchmarking biofuels—a comparison of technical, economic and environmental indicators," *Energy, Sustainability and Society*, 4:20, DOI: 10.1186/s13705-014-0020-x http://energsustainsoc.springeropen.com/articles/10.1186/s13705-014-0020-x

NHTSA (National Highway Traffic Safety Administration), National Center for Statistics and Analysis, 2006. *Vehicle Survivability and Travel Mileage Schedules*. http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf

Shuster, E., et al., 2013. *Analysis of Natural Gas-to-Liquid Transportation Fuels via Fischer-Tropsch*. Report DOE/NETL-2013/1597, National Energy Technology Laboratory. http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Gas-to-Liquids_Report.pdf

SAE (Society for Automotive Engineers) International, 2010. *Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data*. http://standards.sae.org/j2841_201009/

4 FUEL PATHWAYS: GHG ASSUMPTIONS AND DATA SOURCES

4.1 PETROLEUM PATHWAYS

The lifecycle of petroleum fuels begins with petroleum recovery in oil fields and ends with fuel combustion in vehicles. The key stages in the WTW pathway of petroleum fuels are (1) petroleum recovery in oil fields, (2) petroleum refining, and (3) fuel use in vehicles. Besides recovery and production-related activities, all transportation-related activities involved in moving goods from one location to another (e.g., crude oil from oil fields to petroleum refineries and fuel from refineries to refueling sites) are also included. Infrastructure-related activities (e.g., construction of drilling rigs and petroleum refineries) are not included in this study. Figure 3 shows the LCA system boundary and key stages and activities associated with the petroleum fuel pathway.

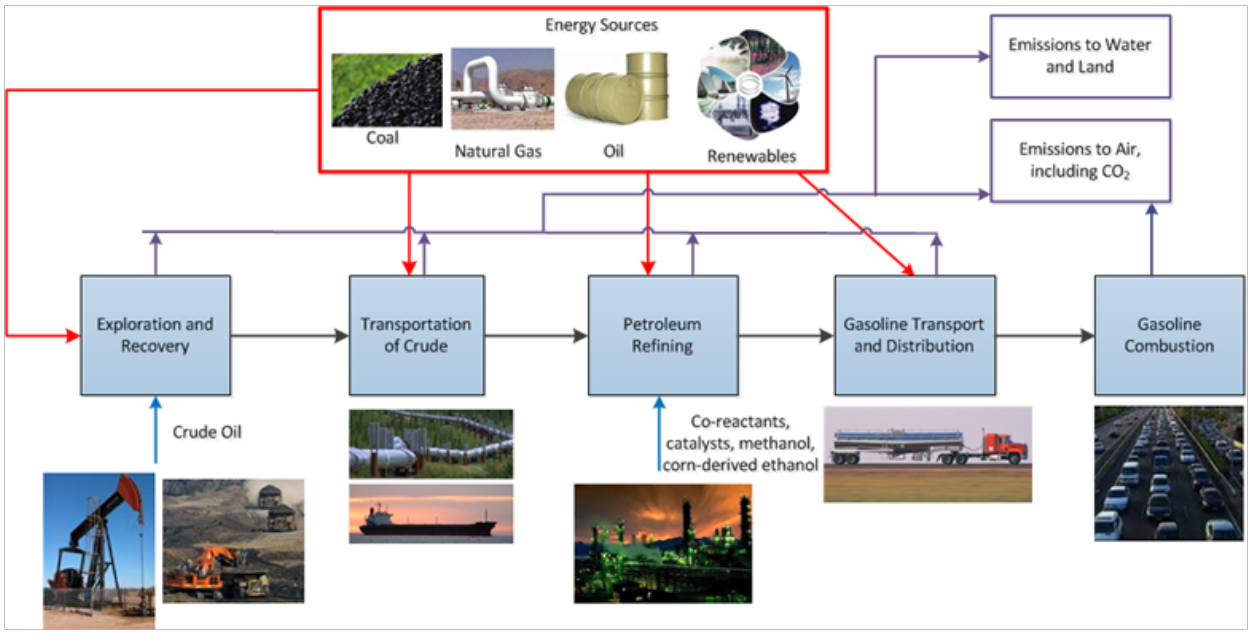

Figure 3. Key stages and activities of the petroleum fuels pathway (gasoline as example)

The petroleum recovery stage includes oil extraction and pretreatment. In some fields, associated gas is a byproduct of crude oil recovery, containing significant amounts of methane (CH_4), which is a potent GHG with a global warming potential 30 times that of CO_2 (assuming a 100-year global warming impact) (Myhre et al. 2013). While the energy efficiency calculated for petroleum recovery does not account for the energy in the portion of the gas that may be flared and vented because it is not an intended energy source, the emissions associated with gas flaring and venting are taken into account in GREET lifecycle modeling.

Domestic petroleum production accounted for 49.1% of total U.S. crude oil consumption in 2012. U.S. crude oil imports are shown in Table 7 (EIA 2014b). Canadian oil sands production is projected to grow from 1.95 million bbl/day in 2013 to 4.81 million bbl/day by 2030. Accounting for 9.4% of the total crude oil processed in U.S. refineries in 2013, the supply of Canadian oil sands crude to U.S. refineries is forecasted to reach 13.6% of total production in 2020, which is used in GREET for CURRENT TECHNOLOGY and FUTURE TECHNOLOGY estimates of oil sands shares (Cai et al. 2015).

Table 7. Crude oil sources in the U.S. (EIA 2014b)

Case	U.S.	Canada	Mexico	Middle East	Latin America	Africa	Other
Crude oil production/ imports (1,000 bbl)	2,719,584	941,236	310,402	730,192	549,484	234,711	55,455
CURRENT TECHNOLOGY (% share)	49.1	17.0	5.6	13.2	9.9	4.2	1.0
FUTURE TECHNOLOGY (% share)	46.7	22.4	6.5	5.7	8.4	8.1	2.2

4.1.1 Crude Production

Crude oil resources around the world vary significantly in regard to quality and production methods, resulting in significant variation in GHG emission intensities associated with crude recovery. Average petroleum recovery efficiency in GREET is 98% based on estimates provided by Brinkman et al. (2005). The energy efficiencies of extraction and upgrading of bitumen from oil sands via surface mining and *in situ* production are estimated by Argonne based on detailed characterization of the energy intensities of 27 oil sands projects, representing industrial practices from 2008 to 2012 (Englander et al. 2014). Four major oil sands production pathways were examined, including bitumen and synthetic crude oil (SCO) production from both surface mining and *in situ* projects. These four pathways are surface mining SCO (M+SCO), *in situ* bitumen (IS+B), surface mining bitumen (M+B), and *in situ* SCO (IS+SCO). They were considered separately to evaluate the impact of differences in oil sands production technologies and types of products on energy and emission intensities. Table 8 shows the energy consumption intensity for these four pathways, along with that for conventional crude (Cai et al. 2014).

Table 8. Energy intensities (MJ/MJ) of extraction and separation, upgrading, and crude transportation for the four oil sands pathways, compared to those of the U.S. conventional crudes pathway (Cai et al. 2014)

Activity	M+B	M+SCO	IS+B	IS+SCO	Oil Sands Weighted Average	Conventional Crude
Bitumen extraction and separation	0.080	0.080	0.20	0.20	0.15	0.020
Cyclic steam stimulation (47%)	–	–	0.23	0.23	–	–
Steam-assisted gravity drainage (53%)	–	–	0.17	0.17	–	–
Bitumen upgrading	–	0.23		0.20	0.11	–
Crude transportation	0.026	0.018	0.026	0.018	0.022	0.015

4.1.2 GHG Emissions in Oil Fields

Methane associated with crude oil production may be used as fuel on site; separated and captured for sale; reinjected into the formation; converted to CO_2 in a flare; or vented directly to the atmosphere. The EPA conducted a comprehensive evaluation of CH_4 emissions from U.S. petroleum systems and developed CH_4 emission factors for 33 venting and fugitive activities in crude oil production fields (Cai et al. 2014; EPA 2014). The EPA approach also estimated venting and fugitive CO_2 emission factors by multiplying CH_4 emissions factors by a conversion factor representing the volumetric ratio of CO_2 to CH_4 content in each activity. The ratios of CO_2 to CH_4 in Table 9 are used to calculate CO_2 emissions for various activities, which include whole crude oil leaks downstream, associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil, and gas emissions from offshore oil platforms (Cai et al. 2014).

Table 9. Ratios of CO_2 to CH_4 volume in emissions from petroleum production fields (Cai et al. 2014)

Emissions	Whole Crude, Post-separator	Associated Gas	Tank Flash Gas	Offshore
CO_2/CH_4, by volume	0.052	0.020	0.017	0.004

EPA estimates the CH_4 emissions from flaring of associated gas using an estimated flaring efficiency of 98% (i.e., assuming that 2% of the CH_4 in the associated gas is unburned and released to the atmosphere). However, the CO_2 emissions from associated gas flaring are not reported by EPA (2014).

Vented and fugitive CH_4 and CO_2 emissions per MMBtu of crude produced were estimated by Cai et al. (2014) using the EPA's bottom-up Tier 2 approach for 12 activities associated with crude oil production:

$$EF_{ANL} = \frac{\sum_i \left(EF_{EPA,i} \times A_i\right)}{(P \times LHV)} \tag{1}$$

where:

$EF_{EPA,i}$ is the EPA emission factor of CH_4 or CO_2 for activity or equipment item *i*;

A_i is the activity data or equipment count for activity or equipment item *i*;

P is the total crude oil production in barrels;

LHV is the lower heating value of crude oil in MMBtu per barrel, which is 5.446 MMBtu/barrel (Argonne 2014); and

EF_{ANL} is the Argonne estimate of the emission factor of CH_4 or CO_2 in grams per MMBtu of crude production.

For oil imported to the United States, there are no bottom-up available estimates of vented, flaring, and fugitive (VFF) GHG emissions for oil produced in other countries or regions. Cai et al. (2014) reported that the volume of associated gas flared in the top 20 flaring foreign countries is comparable to the U.S. volume (3.4 m^3/bbl).

Cai et al. (2014) estimated a flaring CH_4 and CO_2 emission factor of about 0.5 and 89.4 g/MMBtu of U.S. crude oil produced, respectively, based on the physical properties of the associated gas shown in Table 10. Table 11 summarizes the VFF CH_4 and CO_2 emission factors (Cai et al. 2014). The total VFF CH_4 and CO_2 emission factors are 108 and 120 g/MMBtu, respectively, for all crude oil processed in U.S. refineries in 2012 (Cai et al. 2014). These estimates have been incorporated into GREET 2014.

Table 10. Properties of gas flared and vented during crude oil production[a]

Property	Value
Density	877 g/m^3
Total carbon	70.3%
CO_2	13.4% (by weight)
CH_4	68.4% (by weight)

[a] Calculated using the oil production greenhouse gas emissions estimator (OPGEE) tool.

Table 11. VFF CH_4 and CO_2 emission factors from U.S. crude oil production (g/MMBtu of crude)

Factor	VFF CH_4	VFF CO_2
Venting emission	103	30
Flaring emission	0.5	89
Fugitive emission	4	0.2
Total VFF emission	108	120

4.1.3 Crude Refining

The energy consumption by the refining industry in 2012 represented approximately 10% of the total energy supplied to U.S. refineries (EIA 2013b). Argonne employed results from a linear programming model to conduct in-depth analysis of 43 large U.S. refineries, each with a refining capacity greater than 100,000 bbl/day. Although the 43 refineries represented only 31% of the total 139 operating refineries in the United States, they represented 70% of the total U.S. refining capacity and spanned a wide range of crude sources/quality, product slates, and refinery complexity in different Petroleum Administration for Defense District (PADD) regions (Elgowainy et al. 2014). Refinery energy inputs and their derivatives propagate through successive process units to produce intermediate products and, eventually, the final products. Thus, each stream's energy through a process unit carries certain energy and emissions burdens associated with the overall refinery inputs. By estimating the production energy intensity of all streams and aggregating them for the different streams that make various final product pools (e.g., gasoline pool, distillate pool), Argonne estimated the product-specific efficiencies for each product pool. The methodology for distributing the overall refinery energy use and emissions among various refinery products to calculate each product-specific energy and GHG emission intensities is described in Elgowainy et al. (2014). Table 12 shows the details of process fuel use per unit fuel produced for major refinery fuel products.

The energy use and emissions associated with each transportation mode for conventional crude and oil sands products to U.S. refineries, and the transportation and distribution of refined products to refueling stations, are provided in Dunn et al. (2013). The fuel use in vehicles and associated GHG emissions are determined primarily by the vehicle's fuel economy (see Section 6).

Table 12. Refinery Process Fuel Use for Major Fuel Products ($kJ_{process\ fuel}/MJ_{fuel\ product}$)

Process Fuel		Gasoline	Diesel	LPG (Propane)
Purchased fuels	NG – SMR	8.81	17.2	8.49
	NG – combustion	54.1	35.1	36.1
	Electricity	4.01	3.24	2.98
	H_2	6.33	13.0	7.10
Internally produced fuels	Fuel gas combustion[a]	38.5	22.9	25.1
	Catalytic coke combustion	22.5	8.74	28.2

[a] Fuel gas is combined with natural gas in GREET and defined as "still gas."

4.2 NATURAL GAS PATHWAY

The life cycle of NG for use in CNG vehicles begins with the gas recovery in fields and ends with fuel combustion in vehicles. The key stages in the WTW pathway of CNG are: (1) recovery and gathering in gas fields, (2) processing, (3) transmission and distribution, and (4) fuel use in vehicles. Infrastructure-related activities (e.g., construction of drilling rigs, pipelines, and processing plants) are not included in this study. Figure 4 shows the WTW system boundary and key stages and activities associated with the CNG pathway.

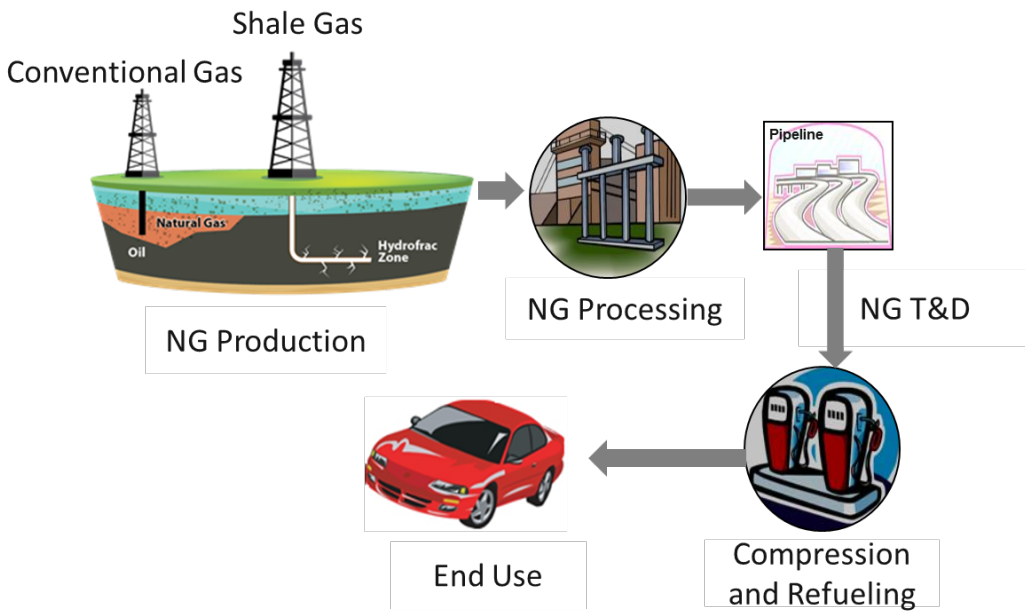

Figure 4. Key stages and activities of the CNG pathway

In gas fields, NG is extracted from underground and transmitted to processing plants via gathering pipelines. At processing plants, NG liquids and impurities are removed from the wet gas to produce pipeline-quality gas. The gas recovery stage includes the extraction of gas from underground and transportation to processing plants. During this stage, fugitive CH_4 is emitted to the atmosphere. The gas processing stage includes cleaning the raw gas to meet specifications of transmission pipelines. On the basis of published data and previous inputs from energy companies, the energy efficiencies for gas recovery and processing were assumed to be 97.2% (Brinkman et al. 2005).

Argonne used CH_4 emissions data from the EPA's 2014 GHG inventory (EPA 2014) to estimate the lifecycle GHG emission impacts of various stages and activities of the NG pathway (Burnham et al. 2014). Several studies demonstrated some shortcomings in the EPA's CH_4 inventory, which has discrepancies with atmospheric measurements (top-down approach) of CH_4 emissions from gas fields. However, the EPA's inventory remains the best publicly available data source for emissions from specific activities.

Table 13 summarizes the CH_4 fugitive emissions for both shale and conventional gas in GREET based on EPA (2014). Table 14 compares the CH_4 leakage rate based on NG throughput by stage from several EPA reports with those used in the GREET 2014. The EPA estimates of CH_4 emissions have decreased significantly since its 2011 inventory, while top-down analyses suggest that these emissions are higher, as noted above (Burnham et al. 2014). Argonne continues to update GREET based on the most recent available research data that reduce the discrepancies between bottom-up and top-down estimates of CH_4 emissions from the NG system.

Table 13. Summary of CH_4 emission factors by activity in GREET 2014 (g CH_4/MMBtu NG) (Burnham et al. 2014)

Sector	Process	Shale Gas	Conventional Gas
Production	Completion	12.4	0.5
	Workover	2.5	0.0
	Liquid unloading	10.4	10.4
	Well equipment	51.3	51.3
Processing	Processing	26.7	26.7
Transmission	Transmission and storage	81.2	81.2
Distribution	Distribution (station pathway)	63.6	63.6
Total		248.1	233.8

Table 14. GREET and EPA CH_4 leakage rate based on NG throughput by stage (%)

Stage	EPA Inventory 2012 Data (2014)	GREET Shale Gas (2014)	GREET Conv. Gas (2014)
Gas field	0.34	0.37	0.30
Completion/workover	–	0.07	0.003
Unloading	–	0.05	0.05
Other sources	–	0.25	0.25
Processing	0.13	0.13	0.13
Transmission	0.39	0.39	0.39
Distribution	0.30	0.30	0.30
Total	1.16	1.19	1.13

4.3 BIOFUELS PATHWAYS

GREET examines the production of biofuels from a variety of feedstock sources, including corn, cellulosic ethanol via fermentation of sugar in starch and cellulose, bio-gasoline via fast pyrolysis of cellulosic biomass, and the production of FAME (biodiesel) and HRD from soybeans. The lifecycles of biofuels contain such activities as fertilizer production, farming, and conversion of feedstock to biofuel, all of which consume fossil energy and produce GHG emissions. According to DOE (2011), the total annual biomass that could be produced, which includes both current and potential biomass from forest and agriculture lands, as well as biomass from energy crops, ranges from 1.094 to 1.633 billion dry tons, depending on the yield assumed for energy crops. Assuming fuel production yield of 80 gal/dry ton, the annual potential capacity for biofuel production is in the order of 88–130 billion gal.

4.3.1 Corn Ethanol

Figure 5 shows the system boundary of the bio-ethanol pathways in the GREET model. Corn farming and ethanol production are the two major direct GHG emission sources in the corn ethanol pathway (Wang et al. 2012). In the farming stage, N_2O emissions from the nitrification and denitrification of nitrogen fertilizer in cornfields is a major GHG emissions source. Natural gas use for fertilizer production and fossil fuel use by farming machinery are also significant GHG emission sources. In corn ethanol plants, GHG emissions result from the use of fossil fuels, primarily NG. GREET takes into account GHG emissions from NG production and distribution to fertilizer and ethanol plants (see Section 4.2).

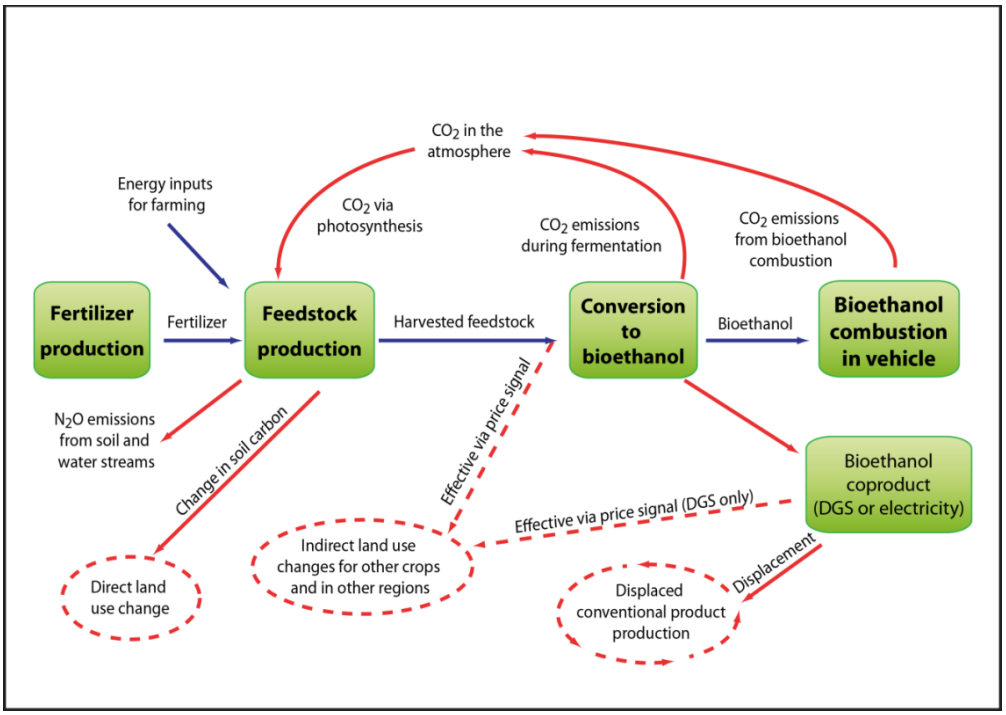

Figure 5. Bio-ethanol pathway activities in GREET

Distillers' grains and solubles (DGS) are a valuable coproduct from corn dry milling ethanol plants (Wang et al. 2012). GREET allocates the ethanol plant energy use and emissions to ethanol (main product) and uses the displacement (substitution) method to calculate credits of the DGS co-product assuming that it displaces animal feed (corn, soybean meal, and urea). More than 80% of dry mill plants co-produce corn oil at an average production rate of 0.53 lb of oil per bushel of corn, or 0.19 lb/gal of ethanol (Wang et al. 2014). GREET 2014 was updated to include an ethanol production pathway with corn oil recovery from dry mill plants. Table 15 shows the assumptions for key parameters in GREET for corn-based ethanol for 2010 (Wang et al. 2012, 2014). The corresponding estimates for 2015 based on GREET default assumptions for increased farming fertilizer use over time are shown in Section A.2.

4.3.2 Corn Stover Ethanol

Corn stover, an agriculture residue of growing corn, can be used as a cellulosic feedstock for biofuels production. The yield of corn stover in cornfields is consistent with corn grain yield on a dry matter basis. A corn grain yield of 10 tonnes (with 15% moisture content) per hectare results in a corresponding corn stover yield of about 8.5 tonnes (dry) (Wang et al. 2012). Several studies concluded that about 1/3–½ of corn stover can be sustainably removed, i.e., without causing erosion or deterioration of the soil quality (Sheehan et al. 2008; DOE 2011; Wang et al. 2012). Stover removal results in the removal of N, P, and K nutrients; thus, the nutrients lost with the stover removal are typically replenished with synthetic fertilizers. The replacement rates based on data for nutrients contained in harvested corn stover are estimated by Han et al. (2011). In this study, we account for the N_2O emissions associated with the supplemental N fertilizer use. We also account for the energy used for corn stover collection and transportation to the ethanol plant (see Table 16).

Table 15. Assumptions for the corn ethanol production pathway used in GREET 2014

Parameter	Value
Corn farming: per bushel of corn (except as noted) – 2010	
Energy use for corn farming[a]	9,600 Btu
N fertilizer application[b]	420 g
P_2O_5 fertilizer application[b]	150 g
K_2O fertilizer application[b]	150 g
Limestone application[a]	1,150 g
N_2O conversion rate of N fertilizer[a]	1.525%
NG use per ton of ammonia produced [c]	31,384 MMBtu
Corn ethanol production (Dry Mill Plants) – 2015	
Ethanol yield[a] (without oil extraction)	2.80 gal/bushel of corn
Ethanol plant energy use[a] (without oil extraction)	26,856 Btu/gal of ethanol
DGS yield[a] (without oil extraction)	15.76 dry lb/bushel of corn
Ethanol yield[b] (without oil extraction)	2.82 gal/bushel of corn
Ethanol plant energy use[b] (with oil extraction)	26,421 Btu/gal of ethanol
DGS yield[b] (with oil extraction)	15 dry lb/bushel of corn
Corn oil yield[b] (with oil extraction)	0.53 dry lb/bushel of corn
Share of dry mill plants with oil extraction[b]	80%
Enzyme and Yeast Assumptions	
Enzyme use[a]	0.001 ton/dry ton of corn
Yeast use[a]	0.000358 ton/dry ton of corn

[a] Source: Wang et al. (2012).
[b] Source: Wang et al. (2014).
[c] Source: Johnson et al. (2013).

Table 16. Assumptions for the corn stover ethanol production pathway

Parameter	Value	Source
Corn stover collection per dry tonne of biomass		
Energy use for collection	224 MJ	Wang et al. (2014)
Energy use by loader	4.9 MJ	Wang et al. (2013)
Supplemental N fertilizer	7,716 g	Wang et al. (2013)
Supplemental P fertilizer	2,205 g	Wang et al. (2013)
Supplemental K fertilizer	13,228 g	Wang et al. (2013)
Cellulosic ethanol production per dry tonne of biomass (except as noted) – 2015		
Ethanol yield	313 L	Globe (2010); DOE (2014a)
Electricity yield	240 kWh	Humbird et al. (2011)
Enzyme use	10 g/kg of dry substrate	Dunn et al. (2012a)
Yeast use	2.49 g/kg of dry substrate	Wang et al. (2012)

In cellulosic ethanol plants, feedstocks go through pretreatment with enzymes that break cellulose and hemicellulose into simple sugars for fermentation. The lignin portion of cellulosic feedstocks is assumed to be combusted to generate steam and power using a combined heat and power (CHP) generator. The CHP generator provides process heat and power, while surplus electricity is assumed to be exported to the

grid. The baseline or mid-point yield estimate for this study is based on the Abengoa Bioenergy corn stover biorefinery project in Kansas, which had a yield of 75 gal ethanol/dry ton (Globe 2010; DOE 2014a).

4.3.3 Soybeans to Fatty Acid Methyl Ester and Hydroprocessed Renewable Diesel

The soybean-based biofuels pathways consists of soybean farming, fertilizer production, transportation and crushing for oil extraction, soy oil transesterification to produce FAME or soy oil hydrogenation to produce HRD, and finally biofuel transportation for use in vehicles (see Figure 6). The yield of intermediate products, such as soy oil and soybean meal, are employed to estimate the energy and emissions burden of each product (i.e., FAME and HRD).

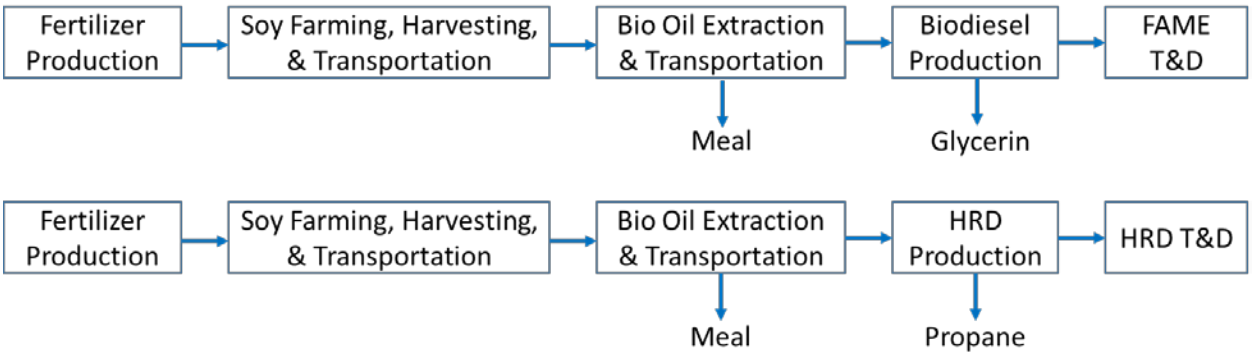

Figure 6. Soybean pathways to produce FAME and HRD

The key parameters of soybean farming in GREET are based on the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture (USDA 2013). NASS conducted surveys on farming practices of various agricultural products and published the 2012 Agricultural Chemical Use Survey among soybean producers in 19 program states (Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Michigan, Minnesota, Mississippi, Missouri, Nebraska, North Carolina, North Dakota, Ohio, South Dakota, Tennessee, Virginia, and Wisconsin). The survey covered 96% of the soybean acreage planted in the United States in 2012 (Han et al. 2014). Tables 17 and 18 present survey data on soybean acreage harvested, production and yield, and the fertilizers and chemicals applied to soybean fields in the 19 program states in 2012 (Han et al. 2014). Table 19 summarizes the calculated fertilizer and chemical application rates for soybean farming in grams/bushel based on the NASS survey. The fuel use for soybean farming is based on a 2006 survey reported by Pradhan et al. (2011). Table 20 presents the soybean farming energy inputs from that survey. The calculated total energy inputs and the share of each process fuel in GREET 2014 are shown in Table 20.

Table 17. Soybean production in 19 program states (USDA 2013; Han et al. 2014)

Year	Area Harvested (Million Acres)	Production (Billion Bushels)	Yield (Bushels/Acre)
2012	73.3	2.92	39.4

Table 18. Fertilizers and chemicals applied to soybean-planted acres in 19 program states (million lb) (USDA 2013; Han et al. 2014)

Year	N Fertilizer	Phosphate	Potash	Herbicide	Insecticide
2012	321	1,329	2,215	133	4.06

Table 19. Fertilizer and chemical application rates for soybean farming (g/bushel) (Han et al. 2014)

Year	N Fertilizer	Phosphate	Potash	Herbicide	Insecticide
2012	49.9	206.7	344.4	20.7	0.6

Table 20. Soybean farming energy inputs (Pradhan et al. 2011; Han et al. 2014)

Fuel	Energy Inputs (per acre)	Energy Inputs (Btu/bushel)
Diesel	3.56 gal/acre	10,684
Gasoline	1.37 gal/acre	3,712
NG	58.59 ft^3/acre	1,346
LPG	0.21 gal/acre	424
Electricity	6.92 kWh/acre	552
Total		16,718

For the FAME and HRD pathways, oil extraction and processing are two key lifecycle stages contributing to energy use and GHG emissions from these pathways. Oil yield is important and depends on the lipid content of the oil seeds. The lipid content of soybean (21% by mass) is low, since a large amount of soy meal (79% by mass) is co-produced. The soy meal is a valuable animal feed and produces large GHG emission credits. Soybean crushing and soy oil transesterification assumptions are adopted from Omni Tech (2010). The Omni Tech data are based on a 2008 survey conducted by the National Biodiesel Board (NBB) covering 37% of the U.S. FAME production (Han et al. 2014). Tables 21 and 22 summarize the key parameters for HRD and FAME production processes.

In HRD production, triglyceride in vegetable oil is hydrogenated to saturate the double-bonds and release the fatty acids from the glycerin backbone. Oxygen in free fatty acids is removed by either hydrodeoxygenation (producing water) or decarboxylation (producing CO_2), thus generating straight-chain alkanes. Straight-chain alkanes are further hydrocracked and isomerized to meet ASTM fuel specifications (Han et al. 2013a). The triglyceride hydrogenation, hydrodeoxygenation, and hydrocracking consume a significant amount of hydrogen, which is a significant GHG emission source when produced from NG via SMR.

The treatment of co-products (such as meal, propane mix, and naphtha) can have a significant impact on the WTW results (Wang et al. 2011). Commonly applied co-product handling methods for fuel production processes are the energy allocation method and the displacement method (also known as substitution or system expansion method). In the energy allocation method, the energy and emissions burdens are allocated to each co-product based on the energy content in each product stream. However, the energy allocation method may not provide meaningful results when the characteristics of the various co-products

Table 21. Assumptions for HRD production from soybeans

Parameter	Value
Oil extraction (Han et al. 2013)	
Oil yield	0.21 lb oil/lb dry soybeans
Meal yield	3.70 dry lb/lb oil
HRD production per tonne of HRD (Huo et al. 2008)	
Oil use	1.174 lb
H_2 use	0.032 lb
NG use	84.0 Btu
Electricity use	93.8 Btu
Propane mix yield	1,096 Btu

Table 22. Soybean crushing and soy oil transesterification assumptions (Omni Tech 2010)

Parameter	Value
Soybean crushing for soy oil production	1.04 lb oil/lb FAME
Energy inputs	
NG	2,068 Btu/lb soy oil
Electricity	447 Btu/lb soy oil
Hexane	59 Btu/lb soy oil
#2 Fuel oil	16 Btu/lb soy oil
#6 Fuel oil	32 Btu/lb soy oil
Coal	1,018 Btu/lb soy oil
Biomass	32 Btu/lb soy oil
Landfill gas	16 Btu/lb soy oil
Total	3,687 Btu/lb soy oil
Soy oil transesterification for FAME production	
Energy inputs	
NG	373 Btu/lb FAME
Electricity	55 Btu/lb FAME
MeOH	785 Btu/lb FAME
Total	1,213 Btu/lb FAME
Material inputs	
Sodium hydroxide	0.4 g/lb FAME
Sodium methoxide	10.5 g/lb FAME
Hydrochloric acid	19.7 g/lb FAME
Phosphoric acid	0.3 g/lb FAME
Citric acid	0.3 g/lb FAME
Glycerin yield	0.120 lb/lb FAME

and their applications are distinct (e.g., co-producing meal and fuel). The displacement method, on the other hand, burdens all energy and emissions to the main product while crediting all energy and emissions associated with the displaced products. Therefore, the displacement method requires that emissions associated with an alternative production pathway be well-defined for the co-products being displaced.

The allocation boundary for co-product handling methods is another important issue for oil seed-based biofuels because co-products are produced in two stages: oil extraction and FAME/HRD production. The oil extraction stage produces meal along with the extracted oil, while the HRD production stage produces propane mix and naphtha in addition to HRD, and the FAME production process co-produces glycerin along with FAME. A system-level approach aggregates the two stages into one stage, thus combining all energy/chemical inputs and co-products into a single process. In this method, the vegetable oil is considered as an intermediate (internal product), and thus the uncertainty of its properties (such as heating or market values) does not affect WTW results. On the other hand, in a process-level approach, energy/chemical inputs and co-products for each stage are treated separately (Han et al. 2013a). The impact of the different allocation methods and system boundary selection are discussed in detail in Wang et al. (2011). GREET uses the process-level approach.

4.3.4 Land Use Change from Biofuel Production

Large-scale biofuels production directly influences domestic land use, which may directly or indirectly induce global land use change (LUC). LUC and other indirect effects of biofuel-related agriculture carry with them inherently high uncertainties related to supply and demand. These effects are usually estimated using agro-economic models, such as the Global Trade Analysis Project (GTAP) developed at Purdue University (Taheripour et al. 2013). When land is converted as a result of producing feedstock for biofuel, impacts include changes in below- and aboveground carbon content. The changes in aboveground biomass are of particular importance when considering the conversion to or from forests. The soil organic carbon (SOC) content may also either decrease or increase, depending on the nature of the crop, soil type, weather, and prior land use. Argonne has developed estimates of domestic and international LUC GHG emission impacts for use in GREET by developing the Carbon Calculator for Land Use Change from Biofuels (CCLUB) production model (Dunn et al. 2014a). In CCLUB, Argonne combines the LUC data generated by GTAP and carbon stocks of land types from three sources. First, SOC changes for the relevant land transitions are estimated with the CENTURY model, which is a soil organic matter model (Kwon et al. 2013). Aboveground carbon stock data for forests comes from the Carbon Online Estimator (COLE) developed by the USDA and the National Council for Air and Stream Improvement (Van Deusen and Heath 2013; Dunn et al. 2014a). Finally, international carbon emission factors for various land types are based on Winrock data for international carbon stock (Dunn et al. 2014a).

The timescale of SOC changes warrants some discussion. SOC for most mature land types is in equilibrium with adjacent carbon stocks (atmospheric, marine, etc.). Conversion of land may cause SOC equilibrium to change. A negative change from the SOC equilibrium position results in carbon release to the atmosphere until the new equilibrium is reached. The time to reach SOC equilibrium depends on many factors and is uncertain but likely on the order of several decades up to 100 years (Wang et al. 2012). A near-term approach (two or three decades) emphasizes near-term events that are more certain. Alternatively some LCA standards advocate a 100-year time horizon for the LCA of any product (BSI 2011). When long time horizons are adopted, future emissions may be discounted, although the methodology for discounting can vary. More recently, Qin et al. (2015) showed that, after most transitions, SOC returns to equilibrium within 20–30 years. CCLUB assumes a 30-year period for both soil carbon modeling and for amortizing total LUC GHG emissions over the biofuel production volume during the same period (Dunn et al. 2014a). This approach aligns with the EPA's LCA methodology for the RFS (EPA 2010b).

For this analysis, the GTAP model was used to calculate LUC used in the GREET model for corn and corn stover ethanol (Dunn et al., 2014a). Other models and calculations using different assumptions and datasets for LUC calculations exist, e.g., the Forest and Agricultural Sector Optimization Model (FASOM) and Food and Agricultural Policy Research Institute (FAPRI) models. They give a wide range of LUC emissions results for the same biofuel pathway. Figure 7 shows estimates for LUC contributions to corn ethanol GHG emissions using different models and assumptions. LUC estimates in the literature are generally lower than the original Searchinger et al. (2008) estimates, but significant variation remains. Land use change is not the explicit subject of this report, so CCLUB/GREET default values are used here in base case analyses (Dunn et al. 2014a; Argonne 2014). The CCLUB modeling used for this study indicates that GHG emissions attributed to U.S. production of corn ethanol is 7.6 g CO_2/MJ of ethanol, while LUC GHG emissions attributed to corn stover ethanol production is -0.65 g CO_2/MJ (Dunn et al. 2014a).

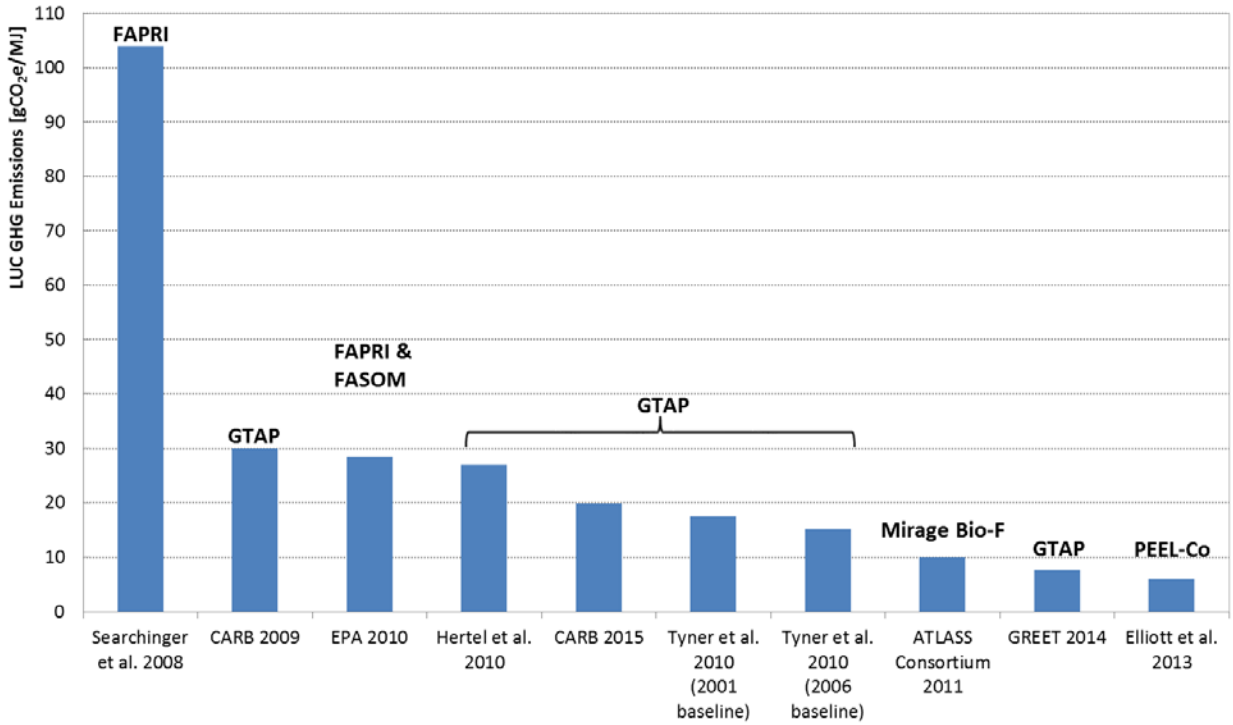

Figure 7. Estimates for LUC contribution to GHG emissions from corn ethanol production

CCLUB does not include LUC GHG modeling for FAME and HRD from soybeans. The CARB estimate for soy FAME biodiesel LUC is 29.1 g CO_2e/MJ (CARB 2015), while the EPA estimate for the same is 33 g CO_2e/MJ (EPA 2010c). Since the yield of HRD is very close to that of the FAME yield per unit mass of soy oil, and given the uncertainty of LUC GHG estimates from CARB and EPA, we assumed the same LUC GHG emissions for both biofuels at 30 g CO_2e/MJ.

4.3.5 Pyrolysis of Cellulosic Biomass

The production of liquid fuels via fast pyrolysis can be divided into three separate processes: the pyrolysis oil production, pyrolysis oil stabilization, and pyrolysis oil upgrading. In the fast pyrolysis of biomass, the incoming biomass undergoes fast decomposition in the absence of oxygen to produce pyrolysis oil, which is condensed and separated from other byproducts. The byproducts of the fast pyrolysis process include fuel gas (mostly CO and CO_2) and biochar.

Figure 8 shows the pathway of fast pyrolysis of cellulosic biomass, specifically forest residue. The total market for waste-wood-to-gasoline technology has been estimated at over 10 billion gal/yr (Gas Technology Institute 2015). The bio-oil produced by the fast pyrolysis process requires subsequent upgrading and refining to produce a mixture of liquid fuels (such as gasoline and diesel). The produced liquid fuels are compatible with the current distribution and refueling infrastructure, and with current ICE technologies (and are thus referred to as “drop-in” fuels). To evaluate the pathways for pyrolysis-based fuels, Argonne relied on a process design case study that characterizes the pyrolysis reaction and the subsequent stabilization and upgrading processes (Jones et al. 2009; Han et al. 2011). The fast pyrolysis processes evaluated by Jones et al. (2009) considered forest residue as feedstock for liquid fuel production.

Fast pyrolysis is performed under a range of temperatures around 500°C and short residence times (few seconds) in the reactor to maximize the pyrolysis oil yield. Liquid fuels from the upgrading of pyrolysis

oil, which is a mixture of naphtha-range products (gasoline blend stock) and diesel-range products (diesel blend stock), do not have infrastructure or engine compatibility concerns. This process contrasts with the much slower gasification process, which provides a high yield of fuel gas that can be synthesized into liquid fuel (e.g., via the Fischer-Tropsch process).

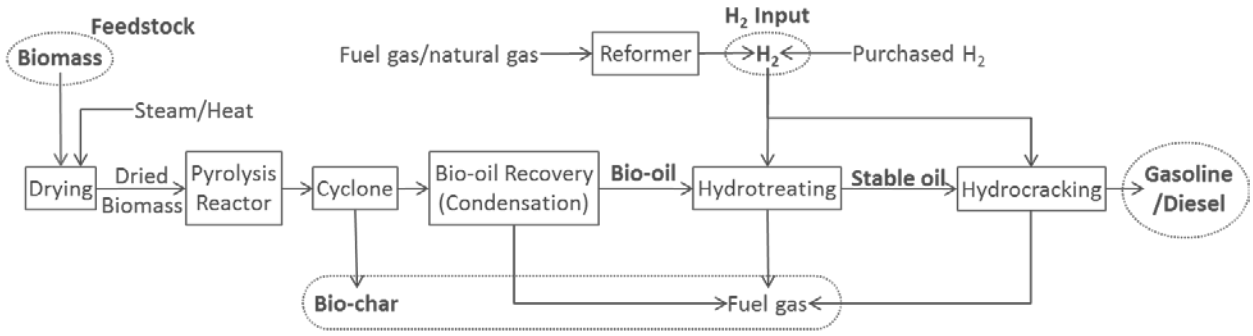

Figure 8. Liquid fuels production from cellulosic biomass via fast pyrolysis

The co-products of the fast pyrolysis process shown in Figure 8 can be used as process inputs to satisfy various energy needs. For example, excess fuel gas and biochar can be combusted to generate electricity, which can be used to grind biomass to a required particle size, while any surplus electricity can be exported to the grid. Alternatively, excess biochar can be exported from the plant and used as a soil amendment, while fuel gas (a mix of CO_2 and C1-C4 gases) can be used to supply process heat or reformed to produce hydrogen for the upgrading processes.

Assuming the same co-product usage as in Jones et al. (2009), all of the biochar and a fraction of the fuel gas from fast pyrolysis of forest residue are combusted to produce the heat for process energy requirements. The remaining fuel gas from the pyrolysis process is used to produce H_2. However, reforming of fuel gas (mostly CO and CO_2) from the pyrolysis process produces a small fraction of the H_2 required for pyrolysis oil stabilization and upgrading. Thus, supplemental H_2 is assumed to be produced onsite or offsite from NG reforming.

Pyrolysis oil is unstable due to its high water, oxygen, and olefin content, which leads to phase separation and polymerization over time. Thus, a hydrotreating step is necessary to remove oxygen and olefin. A hydroprocessing (upgrading) of the stabilized pyrolysis oil is also required to produce liquid fuels, such as gasoline and diesel (Oasmaa and Kuoppala 2003; Diebold 2002). The upgrading of the stable oil into liquid fuels can take place at a biorefinery that is standalone or integrated with the pyrolysis process. Alternatively, the stable oil can be shipped to a petroleum refinery for mixing with other oils/feeds and processing into liquid fuels. For this study, we assume that pyrolysis oil is stabilized and then transported to a petroleum refinery for further processing into liquid fuels (Han et al. 2011).

Key parameters in stabilization and upgrading processes include liquid fuel yields, the process H_2 use, and the fuel gas yield. They depend on the composition of pyrolysis oil and the desired product slates. Table 23 provides the assumptions of the production pathways for fast pyrolysis of forest residue. Details on the calculations of the parameters in Table 23 are discussed in Han et al. (2011). The process energy requirements and yield of liquid fuel for upgrading of pyrolysis oil in a petroleum refinery is assumed to be the same as those for producing petroleum gasoline from crude oil (see Section 4.1.3). The properties of pyrolysis-based gasoline and diesel are assumed to be similar to those of their petroleum-based counterparts.

Table 23. Assumptions about the production of fast-pyrolysis-based liquid fuels from forest residue

Parameter	Value
Forest residue collection and transportation (Wang et al. 2013)	
Energy use for collection	132,180 Btu/dry tonne
Pyrolysis/upgrading process (Han et al. 2011)	
Biomass inputs Electricity use NG for supplemental H_2	3.19 dry lb/lb stable oil 737 Btu/lb stable oil 2,871 Btu/lb stable oil

4.4 Hydrogen Pathways

Hydrogen is an energy carrier that can be produced from various feedstocks and can be converted into electricity with high efficiency in fuel cells to power electric motors for vehicle propulsion. Although H_2 FCEVs emit no GHG or pollutants from the tailpipe, the production of hydrogen—such as from NG via SMR or from grid electricity via electrolysis—can result in emissions upstream of the FCEVs. Furthermore, the light molecular weight of hydrogen requires significant compression and/or cooling to increase its volumetric energy density for transportation, distribution, and refueling (Figure 9). The compression and conditioning of hydrogen requires electricity use, which generates emissions at the power plant. These emissions are accounted for in the WTT stage of the fuel cycle. The H2A models for H_2 production, developed by the National Renewable Energy Laboratory (NREL), and the Hydrogen Delivery Scenario Analysis Model (HDSAM), developed by Argonne, have been used for the pathways considered in this study for FCEVs. The H_2 production models focus on the production processes after biomass or NG are delivered to H_2 production plants. The delivery model includes the compression of H_2 for transmission and distribution and the subsequent compression for vehicle refueling. Data for these processes are incorporated into the GREET 2014 model for evaluating WTW GHG emissions of various H_2 production and delivery pathways. An NREL report has suggested that ample domestic, low-carbon energy resources are available in terms of technical production potential and the proximity of adequate resources to future hydrogen demand centers (Melaina et al. 2013).

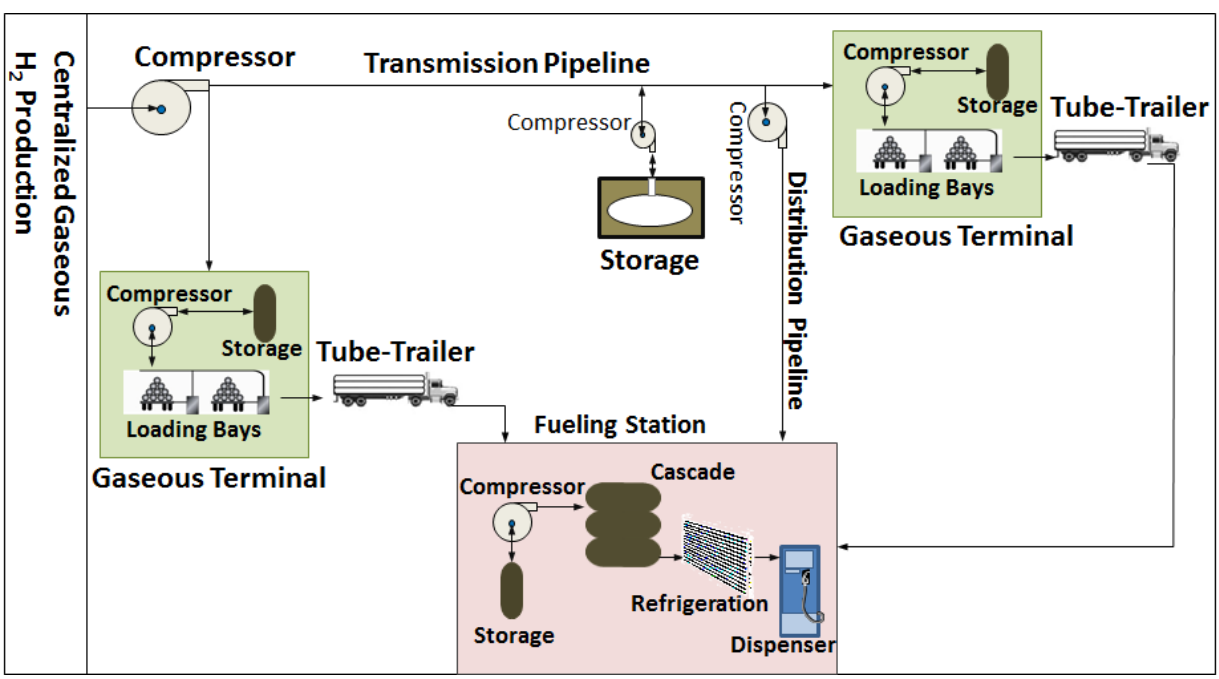

Figure 9. Hydrogen production and delivery pathways

4.4.1 Steam Methane Reforming of Natural Gas

In steam methane reforming, the most common H_2 production process today, high-temperature steam (700–1,000°C) is used to produce H_2 from NG. In the first stage of the process, methane reacts with steam in an endothermic reaction under 3–25 bars of pressure in the presence of a catalyst to produce H_2, CO, and a relatively small amount of CO_2. Subsequently, the CO and steam are reacted by using a catalyst to produce CO_2 and more H_2. Carbon dioxide and other impurities are typically removed from the gas stream by using pressure swing adsorption, leaving essentially pure H_2. Wood et al. (2010) conducted a detailed process engineering modeling of natural gas SMR to produced H_2. The energy balance data from that study implies a H_2 production efficiency of 73% (LHV based). The corresponding efficiency from the H2A H_2 production model is 72%. The H_2 production efficiency in GREET for the two SMR cases of with and without CCS, shown in Table 24, is based on H2A H_2 production model version 3.0 (DOE 2015a). The energy for CCS from the H2A model is 357 kWh/ton of carbon (Elgowainy et al. 2013).

Table 24. Energy efficiency of hydrogen production via SMR

Parameter	without CCS	with CCS
Hydrogen production efficiency	72.0%	70.8%[a]
Production efficiency, not including energy for CCS (GREET format)	72.0%	72.2%
CCS energy	N/A	357 kWh/ton C

[a] H2A model (V3.0) efficiency adjusted to determine the energy for CCS.

4.4.2 Water Electrolysis

Hydrogen can also be produced via electrolysis of water. However, the electrolysis process requires significant amount of electricity, which exceeds the energy in the produced hydrogen. The production efficiency of H_2 via electrolysis based on the H2A model is 66.8% (Elgowainy et al. 2013). The GHG emissions intensity of hydrogen production via water electrolysis depends mainly on the carbon intensity of the used electricity. The desire to minimize GHG emissions associated with H_2 production via electrolysis requires that electricity be generated from renewable sources. Wind power has entered the mainstream utility market because currently available government incentives make it competitive with conventional alternatives. Without a major breakthrough or shift in incentives, wind is likely to remain the lowest-cost source of renewable electricity for H_2 production.

4.4.3 Biomass Gasification

Production of H_2 using biomass feedstocks has attracted increased interest in recent years. Engineering analyses have been performed for a number of gasifier designs and process configurations. The H2A case study for biomass gasification is based on the use of the Battelle-Columbus Laboratory indirectly heated gasifier (Mann and Steward 2012). Details of the design configurations and engineering assumptions used in the H2A model are provided in Ramsden et al. (2013). The biomass feedstock is assumed to be hybrid poplar. The efficiency of H_2 production via gasification of biomass and the process fuel shares in GREET 2014 are shown in Table 25 based on the H2A H_2 production model version 3.0 (Elgowainy et al. 2013).

4.4.4 Hydrogen Delivery (Transmission, Distribution, and Refueling)

The H_2 transmission and distribution in near-term FCEV markets will likely be through trucking, while long-term high-volume transportation economics will favor pipeline H_2 transmission and distribution. GREET assumes that production plants generate H_2 at a pressure of 300 psi (20 bar).

Table 25. Hydrogen production efficiency and process fuel shares for gasification of woody biomass (%)

Parameter	Value
Production efficiency	46.1
Process input share	
Biomass	93.1
NG	4.4
Electricity	2.5

For pipeline delivery, it is assumed the hydrogen pressure is increased to 1,200 psi, similar to current H_2 and NG transmission pipeline pressures, with a compressor to overcome frictional and other losses in the pipeline network. The pipeline transmission and distribution distance is assumed to be 750 mi, similar to that of current NG pipeline networks. The electric energy intensity for pipeline transmission and distribution of H_2 is assumed to be 4,950 Btu/ton-mi. For vehicle refueling, the onboard storage pressure is 10,000 psi (700 bar) at standard temperature. The compressor usually produces pressures that are at least 1.25 times those of storage pressures to account for higher back-pressures as the vehicle onboard storage temperature rises due to heat of compression. GREET assumes that refueling station compressor pressurizes hydrogen from 300 psi to 14,000 psi, resulting in a pressure ratio of 47. The compressor energy per unit mass of H_2 is calculated using Equation (2):

$$\text{Compression Energy, in } \frac{\text{kJ}}{\text{kg}} = Z \times R \times T \times n \times \left(\frac{1}{\eta}\right)\left(\frac{k}{k-1}\right)\left[\left(\frac{P_{outlet}}{P_{inlet}}\right)^{\left(\frac{k-1}{nk}\right)} - 1\right] \quad (2)$$

where:

Z is the mean compressibility factor;
R is the gas constant for hydrogen, in $\frac{\text{kJ}}{\text{kg} \cdot \text{K}}$;
T is the inlet gas temperature, in K;
n is the number of compression stages;
η is the isentropic efficiency of compression;
k is the ratio of specific heats;
P_{outlet} is the compressor discharge pressure, in bar or psi; and
P_{inlet} is the compressor inlet pressure, in bar or psi.

For large compression ratios, such as that for vehicle refueling, the compression is assumed to be done in stages with intercooling of H_2 between stages to keep the compression discharge temperature below a practical limit. The compression pressure ratio per stage is assumed to be 2.1 for H_2. The compression energy equation assumes that the intercooler outlet temperature is equal to the ambient temperature, assumed to be 70°F. The isentropic efficiency for station compressors is assumed to be 65%. Additionally, the efficiency of the electric motor driving the refueling compressor is estimated at 92%. The resulting H_2 refueling compression electric energy consumption is estimated at 3.1 kWh/kg (11,180 kJ/kg).

4.5 GAS-TO-LIQUID (GTL) PATHWAYS

The Fischer-Tropsch synthesis process produces diesel-like hydrocarbon fuel (i.e., FTD) from synthetic gas (syngas), a mixture of CO and H_2. Since the syngas is produced from NG using SMR, this pathway is called gas-to-liquid (GTL). The properties of FTD are similar to those of conventional petroleum diesel. Lifecycle analysis of FTD shows that CCS is needed to achieve significant WTW GHG emissions reduction compared to petroleum diesel. Goellner et al. (2013) conducted a detailed study of GTL FTD production. Based on that study, and using default GREET inputs (e.g., heating values), we calculated a thermal efficiency for GTL production of 61.5% (LHV based) and an overall efficiency of 62.4% when accounting for exported electricity (4.16 kWh/MMBtu of GTL). For the case with CCS, we deduct the electricity required for compression of CO_2 (for injection into a geologic storage) from the exported electricity. The compression energy for CO_2 is calculated using Equation (2) for compression and assuming that CO_2 is compressed from 15 psi to 2,175 psi (supercritical state), with a pressure ratio of 1.7 per stage. The compression isentropic efficiency is assumed at 80% and the electric motor efficiency at 95%. The CO_2 capture ratio (ratio of captured CO_2 to produced CO_2) can reach 91% (Xie et al. 2011). GREET assumes a 90% CO_2 capture ratio to calculate a CCS electricity consumption of 335 kWh/ton of carbon captured.

4.6 ELECTRICITY PATHWAYS

The total electricity generation in the United States has been increasing over the years. The recent trend of fuels consumed for electricity generation show increased shares of NG and renewable power generation and reduced share of coal power generation. Furthermore, recently installed power generation technologies, e.g., NG ACC, have improved energy efficiencies and reduced environmental impacts. Argonne analyzed the generation unit-level data for thermal performance and emissions of electric generating units (EGUs) in 2010, which were published by the EIA and EPA (Cai et al. 2013). Argonne aggregated various EIA and EPA datasets covering plant characteristics, fuel type, and combustion technologies. The aggregated datasets include 10,105 EGUs with combustion information (EIA 2013a), 6,904 EGUs with content of fuels burned (EIA 2013a), and unit-level data on emissions from the EPA's Air Markets Program Data (EPA 2013). GREET estimates unit-level CO_2 emissions using the carbon balance method based on the quantity and carbon content of the fuel consumed by each EGU. The carbon content of the fuels is based on U.S. Geological Survey (USGS) data (USGS 2006) as documented by Cai et al. (2012). Two NREL reports have examined the land use required for wind and solar energy generation (Denholm et al. 2009; Ong et al. 2013).

The electricity generation mix used in this study is representative of the aggregate average generation from all U.S. EGUs. The generation technology shares averaged at the national level for each fuel type are summarized in Table 26 for the years 2013 and 2030. The generation technology shares are determined by the ratio of the amount of electricity generated by each combustion technology to the total electricity generation. The LHV-based energy efficiencies and generation technology shares (for each fuel type) of thermal EGUs in 2010 are shown in Table 27. Table 27 also shows advancement of energy efficiency of various thermal EGUs assumed in GREET (Cai et al. 2013). The electricity transmission and distribution losses are assumed to be 6.5% (Cai et al. 2012).

Table 26. U.S. average generation mix in 2013 and 2030 (%)

Fuel	2013	2030
Residual oil	0.5	0.4
NG	26.1	30.6
Coal	41.5	37.0
Nuclear power	19.5	17.2
Biomass	0.3	1.5
Other renewables	12.2	13.3

Table 27. Energy efficiencies and generation technology shares of thermal EGUs (%)

Fuel	Combustion Technology	Generation Efficiency		Share of Generation Technology by Fuel
		2010	2030	
Coal	Steam cycle	34.7	38.0	99.9
	Integrated gasification combined cycle (IGCC)	34.8	45.0	0.1
NG	Steam cycle	32.3	36.0	11.5
	Combustion turbine	31.6	36.0	5.5
	ACC	50.6	60.0	82.1
	Internal combustion engine	32.8	36.0	0.9
Oil	Steam cycle	33.0	37.0	77.2
	Combustion turbine	29.4	34.0	18.2
	Internal combustion engine	36.3	40.0	4.6
Biomass	Steam cycle	21.9	25.0	100

4.7 CHANGES TO DEFAULT ESTIMATES FROM GREET 2014

The following changes were made to the public release of GREET 2014 for this study.

- **Electricity generation mix:** GREET 2014 incorporated the 2013 generation mixes for 2013 and 2030 from AEO 2014 (EIA 2014a). For this study, GREET 2014 was updated with the 2014 and 2030 generation mixes from AEO 2015, shown in Table 28 (EIA 2015a). The 2014 generation mix was used to represent electricity use in stationary processes along various pathways and for BEV charging in the CURRENT TECHNOLOGY case, while the 2030 generation mix was used only to represent electricity use in stationary processes along various pathways for FUTURE TECHNOLOGY case.

Table 28. 2014 U.S. average generation mix from AEO 2015 (%)

Fuel	2014	2030
Residual oil	0.8	0.8
NG	26.5	32.2
Coal	40.7	35.1
Nuclear power	18.6	16.2
Biomass	1.0	2.3
Other renewables	12.5	13.4

- **Soybean Biofuels LUC GHG emissions**: GREET 2014 does not include LUC GHG emissions for soybean-derived fuels (FAME and HRD). This study includes LUC GHG emissions of 30 g CO_2e/MJ for these pathways, as described above.
- **Co-product handling methods for soybean biodiesel and renewable diesel pathways**: The co-product handling methods for soybean FAME and HRD pathways are changed from the GREET 2014 default method (a process-level hybrid allocation method) to the GREET 2013 default method (a system-level energy allocation method). The change maintained methodological consistency between the previous DOE-published results (Joseck and Ward 2014) and this study.
- **NG recovery and processing electricity consumption**: In GREET 2014, the recovery and processing efficiencies and the electricity process shares were not correctly adjusted when the feed loss (e.g., CH_4 leakage) was reduced. This incorrect adjustment results in the overestimation of electricity consumption for NG recovery and processing. In order to address the issue, the electricity consumptions for NG recovery and processing are corrected as shown in Table 29.

Table 29. NG recovery and processing electricity consumption (Btu/MMBtu)

Model	Conventional Gas Recovery	Shale Gas Recovery	NG Processing
GREET 2014	624	2,382	1,314
C2G	256	244	816

- **Cellulosic ethanol yield and co-produced electricity yield**: The corn stover ethanol yield in GREET 2014 was adjusted from 85 gal/dry ton in 2015 to 75 gal/dry ton to be consistent with the yield reported from the Abengoa Bioenergy corn stover biorefinery project (see Section 4.3.2). The co-generated electricity for export was adjusted from 2.412 kWh/gal to 2.9 kWh/gal of ethanol.

GREET employs time-series tables for many of the key parameters to reflect changes in market shares and technologies over time (e.g., electricity generation mix and electricity generation efficiency). As such, many of the parameters listed above may slightly change with the year selected for simulation in GREET.

4.8 References for Section 4

Argonne National Laboratory, Systems Assessment Group, 2014. *GREET Model, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. https://greet.es.anl.gov/index.php

ATLASS Consortium, 2011. *Assessing the Land Use Change Consequences of European Biofuel Policies*. http://trade.ec.europa.eu/doclib/html/148289.htm

Brinkman, N., M. Wang, T. Weber, T. Darlington, 2005. *GM Study: Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions.* https://greet.es.anl.gov/publication-4mz3q5dw

BSI (British Standards Institution), 2011. *Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services.* British Standard PAS 2050:2011, London, U.K. http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf

Burnham, A., J. Han, A. Elgowainy, and M. Wang, 2014. *Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET1_2014 Model*. https://greet.es.anl.gov/publication-emissions-ng-2014

Cai, H., M.Q. Wang, A. Elgowainy, and J. Han, 2012. *Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors and Their Probability Distribution Functions for Electric Generating Units*. Report ANL/ESD/12-2, Center for Transportation Research, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-updated-elec-emissions

Cai, H., M. Wang, A. Elgowainy, and J. Han, 2013. *Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors of the U.S. Electric Generating Units in 2010*, Argonne National Laboratory. https://greet.es.anl.gov/publication-electricity-13

Cai, H., J. Han, A. Elgowainy, and M. Wang, 2014. *Updated Vented, Flaring, and Fugitive Greenhouse Gas Emissions for Crude Oil Production in the GREET™ Model*. https://greet.es.anl.gov/publication-emissions-crude-oil-2014

Cai H., A.R. Brandt, S. Yeh, J.G. Englander, J. Han, and A. Elgowainy, 2015. "Well-to-Wheels Greenhouse Gas Emissions of Canadian Oil Sands Products: Implications for U.S. Petroleum Fuels," *Environmental Science & Technology*, 49 (13), 8219–8227, DOI: 10.1021/acs.est.5b01255. http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01255

CARB (California Air Resources Board), 2009. "Proposed regulation for implementing low carbon fuel standards," In: *Staff Report: Initial Statement of Reasons*, vol. 1. Sacramento, CA: California Environmental Protection Agency, Air Resources Board; March 5.

CARB, 2015. *Low Carbon Fuel Standard Regulation*. http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

Denholm, P., M. Hand, M. Jackson, and S. Ong, 2009. *Land-Use Requirements of Modern Wind Power Plants in the United States*. Report TP-6A2-45834, NREL. http://www.nrel.gov/docs/fy09osti/45834.pdf

Diebold, J.P., 2002. "A Review of the Chemical and Physical Mechanisms of the Storage Stability of Fast Pyrolysis Bio-oils." In: *Fast Pyrolysis of Biomass: A Handbook*; A. Bridgwater, (ed.), CPL Press: Newbury, U.K., Vol. 2, pp. 243–292.

DOE (U.S. Department of Energy), 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. R.D. Perlack and B.J. Stokes (Leads), Report ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN, 227 pp. http://www.energy.gov/eere/bioenergy/downloads/us-billion-ton-update-biomass-supply-bioenergy-and-bioproducts-industry

DOE, 2014a. *Abengoa*. http://www.energy.gov/eere/bioenergy/abengoa

DOE, Hydrogen and Fuel Cells Program, 2015a. *Production Case Studies*. https://www.hydrogen.energy.gov/h2a_prod_studies.html

Dunn, J.B., S. Mueller, and M.Q. Wang, 2012a. "Energy Consumption and Greenhouse Gas Emissions from Enzyme and Yeast Manufacture for Corn and Cellulosic Ethanol Production." *Biotechnol. Lett.*, doi: 10.1007/s10529-012-1057-6. http://link.springer.com/article/10.1007%2Fs10529-012-1057-6

Dunn, J.B., et al., 2013. Argonne National Laboratory, unpublished information.

Dunn, J.B., Z. Qin, S. Mueller, H. Kwon, M.M. Wander, and M. Wang, 2014a. *Carbon Calculator for Land Use: Change from Biofuels Production (CCLUB)*. Report ANL/ESD/12-5, Rev.2, Argonne National Laboratory. https://greet.es.anl.gov/publication-cclub-manual

EIA (U.S. Energy Information Administration), 2013a. *Form EIA-923 Detailed Data*. http://www.eia.gov/electricity/data/eia923

EIA, 2013b. *Refinery Capacity Report 2013*. Table 10a, Washington, DC. http://www.eia.gov/petroleum/refinerycapacity/archive/2013/table10.pdf

EIA, 2014a. *Annual Energy Outlook 2014 with projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf

EIA, 2014b. *Crude Oil Production*. http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm

EIA, 2015a. *Annual Energy Outlook 2015 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

Elgowainy, A., J. Han, and H. Zhu, 2013. *Updates to Parameters of Hydrogen Production Pathways in GREET*. Research note, Argonne National Laboratory. https://greet.es.anl.gov/publication-h2-13

Elgowainy, A., J. Han, H. Cai, M. Wang, G.S. Forman, and V.B. DiVita, 2014. "Energy Efficiency and Greenhouse Gas Emissions Intensity of Petroleum Products at US Refineries," *Environ. Sci. Technol.*, doi: 10.1021/es5010347. http://pubs.acs.org/doi/abs/10.1021/es5010347

Elliott, J., B. Sharma, N. Best, M. Glotter, J.B. Dunn, I. Foster, F. Miguez, S. Mueller, and M. Wang, 2014. "A Spatial Modeling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions". *Environ. Sci. Technol*., 2014, 48 (4), pp 2488–2496, DOI: 10.1021/es404546r. http://pubs.acs.org/doi/abs/10.1021/es404546r

Englander, J.G., and A.R. Brandt, 2014. *Oil Sands Energy Intensity Analysis for GREET Model Update*.

EPA (U.S. Environmental Protection Agency), 2010b. "Regulations of Fuels and Fuels Additives: Changes to Renewable Fuel Standard Program; Final Rule." *Federal Register*, March 26, Vol. 75 (No. 58): 14670–14904. https://www.federalregister.gov/articles/2010/03/26/2010-3851/regulation-of-fuels-and-fuel-additives-changes-to-renewable-fuel-standard-program

EPA, 2010c. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.* Report EPA-420-R-10-006. http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

EPA, 2013. *Air Markets Program Data*. http://ampd.epa.gov/ampd

EPA, Climate Change Division, 2014. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012*, Report EPA 430-R-14-003, Washington, DC. http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html#fullreport

GTI (Gas Technology Institute), Haldor Topsoe, Andritz, UPM, and Phillips 66, 2015. *Green Gasoline from Wood using Carbona Gasification and Topsoe TIGAS Process.* Final Report DE-EE0002874.

Globe Newswire, 2010. *Abengoa Bioenergy and Mid-Kansas Electric Reach Agreement Concerning First Commercial-Scale Hybrid Cellulosic Ethanol and Power Plant in U.S.* January 19. http://www.globenewswire.com/news-release/2010/01/19/412515/182207/en/Abengoa-Bioenergy-and-Mid-Kansas-Electric-Reach-Agreement-Concerning-First-Commercial-Scale-Hybrid-Cellulosic-Ethanol-and-Power-Plant-in-U-S.html

Goellner, J.F., V. Shah, M.C. Turner, N.J. Kuehn, J. Littlefield, G. Cooney, and J. Marriott, 2013. *Analysis of Natural Gas-to Liquid Transportation Fuels via Fischer-Tropsch*. Report DOE/NETL-2013/1597, National Energy Technology Laboratory. http://netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Gas-to-Liquids_Report.pdf

Han, J., A. Elgowainy, I. Palou-Rivera, J.B. Dunn, and M.Q. Wang, 2011. *Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET*. Report ANL/ESD/11-8, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-wtw_fast_pyrolysis

Han, J., A. Elgowainy, H. Cai, and M. Wang, 2013a. "Life-cycle analysis of bio-based aviation fuels." *Bioresource Technology*, Vol. 150, pp. 447–456, doi:10.1016/j.biortech.2013.07.153. http://www.sciencedirect.com/science/article/pii/S0960852413012297

Han, J, A. Elgowainy, J. Dunn, and M. Wang, 2013b. "Life Cycle Analysis of Fuel Production from Fast Pyrolysis of Biomass." *Bioresource Technology*, Vol. 133, pp. 421–428, doi:10.1016/j.biortech.2013.01.141. http://www.sciencedirect.com/science/article/pii/S0960852413001739

Han, J., A. Elgowainy, H. Cai, and M. Wang, 2014. *Update to Soybean Farming and Biodiesel Production in GREET*. Research Note, Argonne National Laboratory. https://greet.es.anl.gov/publication-soybean-biodiesel-2014

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen, 2010. "Effects of US Maize Ethanol in Global Land Use and greenhouse Gas Emissions: Estimating Market-Mediated Responses." *Bioscience*, 60:223e31.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon, 2011. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*. Report TP-5100-47764, NREL. http://www.nrel.gov/docs/fy11osti/47764.pdf

Huo, H., M. Wang, C. Bloyd, and V. Putsche, 2008. *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*. Report ANL/ESD/08-2, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-e5b5zeb7

Johnson, M., I. Palou-Rivera, and E. Frank, 2013. "Energy Consumption During the Manufacture of Nutrients for Algae Cultivation," *Algal Research*, Vol. 2, Issue 4, pp. 426–436. doi:10.1016/j.algal.2013.08.003. http://dx.doi.org/10.1016/j.algal.2013.08.003

Jones, S.B., C. Valkenburg, C.W. Walton, D.C. Elliott, J.E. Holladay, D.J. Stevens, C. Kinchin, and S. Czernik, 2009. *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case*. Report PNNL-18284, Pacific Northwest National Laboratory, Richland, WA. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18284.pdf

Joseck, F., J. and Ward, 2014. *Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways*. https://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

Kwon, H.-Y., S. Mueller, J.B. Dunn, and M.M. Wander, 2013. "Modeling State-level Soil Carbon Emission Factors under Various Scenarios for Direct Land Use Change Associated with United States Biofuel Feedstock Production." *Biomass and Bioenergy*, 55, 299–310. http://www.sciencedirect.com/science/article/pii/S0961953413000950

Mann, M., and D. Steward, 2012. *Current (2010) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Version 3.0*. National Renewable Energy Laboratory, Golden, CO.

Melaina, M., M. Penev, and D. Heimiller, 2013. *Resource Assessment for Hydrogen Production: Hydrogen Production Potential from Fossil and Renewable Energy Resources*. Report TP-5400-55626, NREL. http://www.nrel.gov/docs/fy13osti/55626.pdf

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013. "Anthropogenic and Natural Radiative Forcing." In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, U.K., and New York, NY. http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf

Oasmaa, A., and E. Kuoppala, 2003. "Fast Pyrolysis of Forestry Residue. 3. Storage Stability of Liquid Fuel." In: *Energy & Fuels 2003*, 17, 1075–1084, doi: 10.1021/ef030011o. http://pubs.acs.org/doi/abs/10.1021/ef030011o

Omni Tech International, 2010. *Life Cycle Impact of Soybean Production and Soy Industrial Products*. United Soybean Board, Chesterfield, MO. http://biodiesel.org/reports/20100201_gen-422.pdf

Ong, S., C. Campbell, P. Denholm, R. Margolis, and G. Heath, 2013. *Land-Use Requirements for Solar Power Plants in the United States*. Report TP-6A20-56290, NREL. http://www.nrel.gov/docs/fy13osti/56290.pdf

Pradhan, A., D.S. Shrestha, A. McAloon, W. Yee, M. Haas, and J.A. Duffield, 2011. "Energy Life-cycle Assessment of Soybean Biodiesel Revisited." *American Society of Agricultural and Biological Engineers*, 54(3), pp. 1031–1039. http://dx.doi.org/10.13031/2013.37088

Qin, Z., J.B. Dunn, H. Kwon, S. Mueller, and M.M. Wander, 2016. "Soil Carbon Sequestration and Land Use Change Associated with Biofuel Production: Empirical Evidence." *GCB Bioenergy*, 8: 66–80, doi:10.1111/gcbb.12237 http://dx.doi.org/10.1111/gcbb.12237

Ramsden, T., M. Ruth, V. Diakov, M. Laffen, and T.A. Timbario, 2013. *Hydrogen Pathways Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios*. Report NREL/TP-6A10-60528, National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy14osti/60528.pdf

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu, 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change," *Science*, 319(5867), pp. 1238–1240, DOI: 10.1126/science.1151861 http://science.sciencemag.org/content/319/5867/1238.abstract

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelsh, 2008. "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol," *J. of Ind. Ecol*., 7(3–4):117–46.

Taheripour, F., and W.E. Tyner, 2013. "Biofuels and Land Use Change: Applying Recent Evidence to Model Estimates." *Applied Sciences*, 3, 14–38. http://www.mdpi.com/2076-3417/3/1/14

Tyner, W.E., F. Taheripour, Q. Zhuang, D. Birur, and U. Baldos, 2010. *Land Use Changes and Consequent CO_2 Emissions Due to US Corn Ethanol Production: A Comprehensive Analysis*. Purdue University, Department of Agricultural Economics. https://www.gtap.agecon.purdue.edu/resources/download/5200.pdf

USDA (U.S. Department of Agriculture), 2013. NA*SS Highlights: 2012 Agricultural Chemical Use Survey, Soybean*. Washington, DC. http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2012_Soybeans_Highlights/ and http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/index.php

USGS (U.S. Geological Survey), 2006. *US Coal Quality Database (Version 2.0), National Coal Resources Data System*. http://energy.er.usgs.gov/products/databases/CoalQual/index.htm

Van Deusen, P., and L.S. Heath, 2013. *COLE Web Applications Suite*. NCASI and USDA Forest Service, Northern Research Station. http://www.ncasi2.org/COLE/

Wang, M., H. Huo, and S. Arora, 2011. "Methods of Dealing with Co-products of Biofuels in Life-cycle Analysis and Consequent Results within the U.S. Context." *Energy Policy*, 39, 5726–5736. http://www.sciencedirect.com/science/article/pii/S0301421510002156

Wang, M., J. Han, J. Dunn, H. Cai, and A. Elgowainy, 2012. "Well-to-wheels Energy Use and Greenhouse Gas Emissions of Ethanol from Corn, Sugarcane and Cellulosic Biomass for US Use." *Environmental Research Letters*, Vol. 7, No. 4, 045905. http://dx.doi.org/10.1088/1748-9326/7/4/045905

Wang, Z., D. Dunn, J. Han, and M. Wang, 2013. *Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels for GREET1_2013*. Report ANL/ESD-13/9, Argonne National Laboratory. https://greet.es.anl.gov/publication-feedstocks-13

Wang, Z., D. Dunn, and M. Wang, 2014. *Updates to the Corn Ethanol Pathway and Development of an Integrated Corn and Corn Stover Ethanol Pathway in the GREET Model*. Report ANL/ESD-14/11, Argonne National Laboratory https://greet.es.anl.gov/publication-update-corn-ethanol-2014

Wood, R.A., R.A. Boardman, M.W. Patterson, and P.M. Mills, 2010. *HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Economic Analysis*. Report TEV-954, Idaho National Laboratory.

Wright, M.M., J.A. Satrio, R.C. Brown, D.E. Daugaard, and D.D. Hsu, 2010. *Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels*. Report NREL/TP-6A20-46586, National Renewable Energy Laboratory, Golden, CO. http://www.nrel.gov/docs/fy11osti/46586.pdf

Xie, X., M. Wang, and J. Han, 2011. "Assessment of Fuel-Cycle Energy Use and Greenhouse Gas Emissions for Fischer-Tropsch Diesel from Coal and Cellulosic Biomass." *Environ. Sci. Technol*., 45, 3047–3053. http://dx.doi.org/10.1021/es1017703

5 FUEL PATHWAYS: COST ASSUMPTIONS AND DATA SOURCES

The cost analysis of fuel pathways investigated in the C2G evaluation was developed from three general sources of publicly available data and models: (1) the EIA's 2015 AEO (EIA 2015a), (2) external cost evaluations, and (3) publicly available alternative fuel costing models that were run using a consistent set of parameters developed by the C2G study group.

5.1 APPROACH, ASSUMPTIONS, AND SUMMARY OF FUEL COSTS

The fuel cost analysis used a variety of models and references to determine the cost to consumers of dispensed fuel (not at the production-plant gate), less federal and state fuel taxes, reported on a $/gge (gallon gasoline equivalent) basis in 2013$.[7] Fuel costs were developed for both the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases (MY2015 and MY2025–2030, respectively). In some instances, a CURRENT TECHNOLOGY, LOW VOLUME cost was also estimated.

In general, cost data were derived from the 2015 AEO (EIA 2015a) and its related reports and data tables, from various TEA models developed by DOE to assess the cost of alternative and renewable fuels, and from additional publicly available reports. Costs in AEO 2015 assume facility profitability after accounting for capital cost, operating cost, and risk factors (EIA 2015b). Where possible, TEA models were revised by the C2G team to use a consistent set of assumptions and financial parameters (see Table 30).

The remainder of this section provides details on how cost modeling was conducted for the fuel pathways investigated in this C2G study, as well as the resulting fuel cost estimates for these pathways. An overview of the fuel assumptions, data sources, and cost results is found in Table 31 and Figure 10. The resulting fuel costs are used in Section 9 as inputs to the LCD evaluation.

Table 30. Common assumptions used in fuel cost modeling

Metric	Assumption
IRR	10%
Dollar value year	2013
Finance rate	All equity
[Facility] depreciation rate	20-year Modified Accelerated Cost Recovery System (MACRS)
Inflation rate	N/A (analysis in real dollars)
Overall tax rate	38.9%
Analysis period (facility life)	40 (30–70) years
[Internal] electricity scenario	AEO 2015 (average grid and new generation sources)
[Internal] NG	AEO 2015
Biomass feedstock(s)	$100+ per short ton (CURRENT TECH) $80 per short ton (FUTURE TECH)
Assumed scale/volume	At/above optimal scale

[7] Gallon gasoline equivalent is a measure based on energy content. In this study, a gge is modeled to contain 112,194 Btu of energy on an LHV basis, coming from 90% gasoline blendstock and 10% (denatured) ethanol on a volume basis.

Table 31. Fuel cost assumptions (2013$/gge)[a]

Fuel		CURRENT TECH	FUTURE TECH (low/base/high)	Notes
Crude oil	$/barrel to refinery	50	57/82/158	EIA AEO 2015 average price to refinery (low oil, Reference case, high oil)
Gasoline	Petroleum	1.80	1.90/2.44/4.04	AEO 2015 (low oil, reference case, and high oil), taxes removed
	Pyrolysis of forest residue		4.17	CURRENT TECH cost based on Jones et al. (2014), FUTURE TECH cost based on 2017 targets, all values updated to be in line with consistent approach and will not exactly match the BETO Multi-Year Progress Plan (MYPP) or design report.
Diesel	Petroleum	1.90	2.01/2.60/4.40	AEO 2015, with fuel taxes removed
	Pyrolysis of forest residue		4.17	CURRENT TECH cost based on Jones et al. (2014), FUTURE TECH cost based on 2017 targets, all values updated to be in line with consistent approach and will not exactly match BETO MYPP or design report
	FAME (B20)		2.12/2.72/4.37	IRENA (2013) adjusted for soy oil feed cost. FAME (B100) FUTURE TECH Cost: $2.63/3.25/4.25 per gge
	HRD		3.77/4.24/5.27	Based on Pearlson (2013)
	GTL		4.14	Based on Shuster et al. (2013); CURRENT TECH without CCS, FUTURE TECH with CCS
CNG	CNG	2.04	1.95/2.02/2.51	AEO 2015 (low oil, reference, and high oil), taxes removed
Propane	LPG	2.17	2.26/2.49/2.98	EIA AEO 2015 (low oil, reference, and high oil), taxes removed
Ethanol	E85 (corn)	2.21		AEO 2015, taxes removed
	E85 (corn stover)		4.18/4.69/4.88	FUTURE TECH (2025) cost projection uses C2G financing assumptions with yield, capital expenditure ratios, and capacity utilization assumptions based on available data from pilot, demonstration, and commercial plants. A contingency of 30% of total capital costs was added. Cost results and assumptions do not match BETO MYPP or design report.
Electricity	Average mix	3.98		AEO 2015 (average grid mix)
	NG ACC		4.52	AEO 2015, new electricity generation resources
	ACC w/CCS		5.43	AEO 2015, new electricity generation resources
	Wind		4.56	AEO 2015, new electricity generation resources
	Solar PV		5.90	AEO 2015, new electricity generation resources
Hydrogen	NG SMR	4.90 (HIGH-VOLUME) /9.10 (LOW-VOLUME)	4.59	H2A + HDSAM (CURRENT TECH without CCS; FUTURE TECH with CCS)
	Electrolysis		7.41	H2A + HDSAM (FUTURE TECH with electricity from wind, solar, and ACC with CCS)
	Biomass gasification		4.78	H2A (BETO MYPP prices) + HDSAM

[a] The central value is the base case for this study when multiple costs are listed, and low/high values are used for sensitivity analyses. For AEO 2015-sourced data, the base case corresponds to the AEO 2015 reference case.

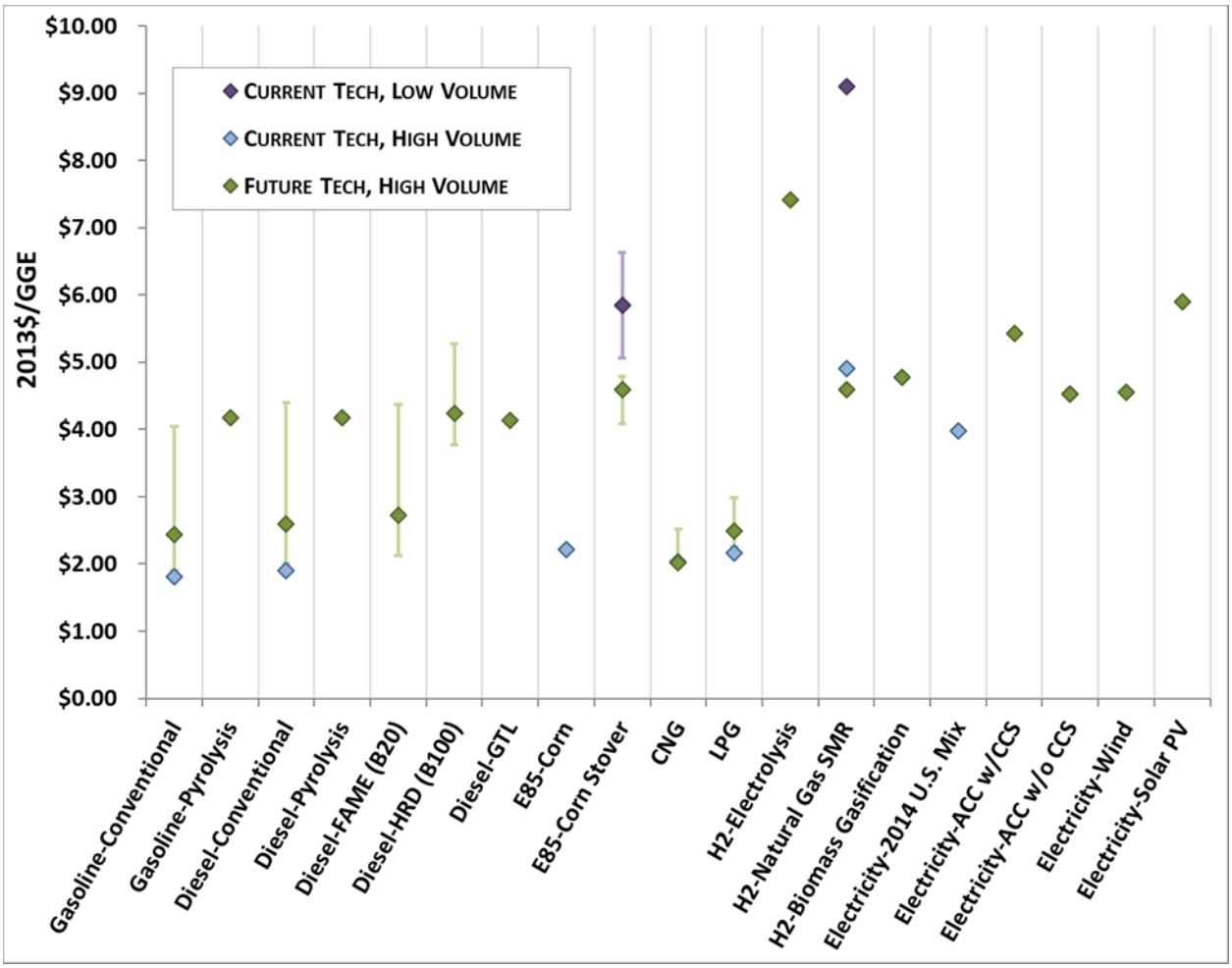

Figure 10. Summary of fuel cost results

5.2 TRANSPORTATION FUEL PRICE ESTIMATES FROM AEO 2015

Fuel costs for conventional gasoline, conventional diesel, ethanol (E85) from corn (starch), CNG, and LPG were based on AEO 2015. In particular, the AEO 2015 reference case "Energy Prices by Sector and Source" data were used to provide base case fuel costs in the C2G study for the CURRENT TECHNOLOGY (2015) and FUTURE TECHNOLOGY (2025–2030) cases. High and low fuel costs for the FUTURE TECHNOLOGY case were based on the AEO 2015 "High Oil Price" and "Low Oil Price" estimates, respectively, and are used for sensitivity analysis in Sections 9.3 and 10.4.

AEO 2015 price data are provided in 2013$, with fuel prices provided in $/MMBtu. AEO price estimates also include highway fuel taxes. To obtain fuel prices in $/gge excluding taxes (standard assumptions for this study), AEO fuel prices were revised as follows:

- Prices were converted from $/MMBtu to $/gge based on LHV fuel energy content data.
- Highway fuel taxes were removed, using American Petroleum Institute data on state and federal highway fuel taxes (API 2014).

As AEO 2015 prices depict fuel prices delivered to consumers, no additional costs for distribution and dispensing were included.

5.3 PYROLYSIS FUELS

This study analyzes both gasoline and diesel pyrolysis fuel pathways for the FUTURE TECHNOLOGY, HIGH VOLUME case. These pathways assume a 100% pyrolysis fuel is used. Pyrolysis fuel costs are based on Jones et al. (2014), which includes projections to 2017. The pyrolysis fuel pricing for the FUTURE TECHNOLOGY, HIGH VOLUME case is based on Jones et al.'s 2017 projection, with costs modeled for n^{th} plant designs using mature technologies.

The cost of the pyrolysis oil is based on a design case by Jones et al. (2013), which details the conversion of biomass through a thermochemical pyrolysis pathway followed by hydroprocessing to produce hydrocarbon blendstocks (gasoline- to diesel-range fuels). The original costs were modified to be consistent and comparable to other C2G analyses and vary from values reported in both the design cases and the reported values in the DOE Bioenergy Technologies Office (BETO) MYPP (DOE 2014b). Namely, the financial assumptions were modified to assume 100% equity financed, as well as an overall tax rate of 38.9%. Additionally, the processed feedstock costs were modified by adopting the projections for the AEO 2014 basis for natural gas and electricity inputs (EIA 2014a).[8] Finally the cost year dollar case was modified from 2011$ to 2013$.

The revised cost of pyrolysis fuel based on Jones et al. (2014) was estimated to be $3.75/gge in 2025 (2013$), produced at the plant gate. Since this projection is a plant-gate cost, this C2G study includes an additional cost for distribution and dispensing. The distribution and dispensing cost is based on a 2013 International Energy Agency (IEA) study on the production costs of alternative fuels (Cazzola et al. 2013). The IEA study provides transport and storage and dispensing costs for a variety of alternative transportation fuels, with estimates for a low oil price case (US$60/bbl) and a high oil price case (US$150/bbl). This study uses the average of these cost estimates for the distribution and dispensing cost. For biomass pyrolysis fuels, the distribution cost is $3.55/GJ or $0.42/gge. Together with the plant-gate production cost, this yields a dispensed cost of pyrolysis gasoline or diesel of $4.17/gge for 2025.

Note that the modeled costs for pyrolysis gasoline and pyrolysis diesel are the same, though the estimated costs of conventional gasoline and conventional diesel, which are based on AEO 2015 data, differ. While AEO modeling of conventional gasoline and diesel costs take into consideration both supply and demand, the models for pyrolysis products did not consider product slates or market forces. Therefore, pyrolysis gasoline and pyrolysis diesel were assumed to have equal costs.

5.4 FUTURE TECHNOLOGY DIESEL FUELS (HRD, FAME, GTL/FTD)

Beyond the conventional and pyrolysis diesel fuels described above, the C2G study investigates several other advanced and bio-derived diesel fuel pathways for the FUTURE TECHNOLOGY case. Cost assumptions for these diesel pathways are described below.

---

[8] The analysis for this report was initiated in 2014 using fuel costs from AEO 2014 (EIA 2014a). Crude oil prices fell in 2014 and 2015, resulting in lower price projections for gasoline and petroleum diesel in AEO 2015 (EIA 2015a). In addition, the price for E85 fell between 2014 and 2015 (see Table F.1 for a comparison of AEO 2014 and AEO 2015 fuel costs). We updated all fuel costs that are priced directly in AEO (gasoline, diesel, CNG, LPG, E85 from corn [CURRENT TECHNOLOGY case], and electricity) to AEO 2015 values. Feedstock and utility prices for production of H_2 from NG SMR, biomass gasification, and wind electrolysis used AEO 2015 values as well. Prices used in this study for GTL FTD, FAME (B20), and HRD (B100) were taken from external modeling/reports, do not include AEO data, and hence were not updated using AEO pricing (which is not relevant). Fuel costs for H_2 delivery, E85 from corn stover (FUTURE TECHNOLOGY), and pyrolysis gasoline/diesel were modeled as part of this study using utility (electricity and NG) costs from AEO 2014. The effect of updating the utility costs to AEO 2015 values was determined to have a negligible impact (<1%) on the LCD and carbon abatement costs for these pathways; we did not revise the analysis for these fuels.

5.4.1 Hydroprocessed Renewable Diesel (HRD) Pathway

This C2G study includes a 100% HRD biodiesel (B100) pathway based on the hydroprocessing of soybeans.

Cost estimates for the HRD diesel pathway come from a 2013 Massachusetts Institute of Technology (MIT) study (Pearlson et al. 2013), which considered a range of facility sizes modeled to produce alternative fuels from hydroprocessed fatty acids. The analysis uses a discounted cash flow, rate-of-return methodology to determine plant-gate fuel production prices. The MIT results were reported in $/L of fuel. When converted to 2013$ and $/gge based on LHV energy content, the average plant-gate cost of HRD-based diesel is $4.02/gge. As with the pyrolysis fuels, distribution and dispensing costs were added, based on the 2013 IEA alternative fuels study, which indicates a cost of $0.22/gge for distribution and dispensing of biodiesel fuels. Including these distribution costs, the C2G study assumes a cost of $4.24/gge for dispensed HRD diesel (B100) in 2025, with a cost range of $3.77/gge to $5.27/gge.

5.4.2 Fatty Acid Methyl Ester (FAME) Pathway

The FAME pathway in the C2G study is modeled as a B20 diesel fuel: 20% by volume bio-diesel (FAME) and 80% by volume conventional low-sulfur diesel. Costs for the conventional low-sulfur diesel fuel portion is based on the AEO 2015 price for diesel fuel in 2025, less fuel taxes, in 2013$.

FAME bio-diesel costs were based on a 2013 International Renewable Energy Agency (IRENA 2013) study on renewable fuel costs. The IRENA study reported a soybean-based FAME B100 cost of $1.01/L of diesel equivalent given a soy oil feedstock of $0.82/L ($893/tonne) (reported in 2012$). Projected bio-diesel costs from IRENA were adjusted to reflect a soy oil feedstock cost consistent with the 2013 MIT study used in the cost estimation of HRD (Pearlson et al. 2013). Adjusting to this lower soy feedstock cost ($0.74/L in 2013$) and using the same capital and operations and maintenance costs, the revised IRENA bio-diesel cost is $0.91/L diesel equivalent. A low-high cost range was developed using the data from IRENA 2013 based on a range of soy oil feedstock cost of $600 to $1,100/tonne ($0.55 to $1.01/L). Based on this soy feedstock range, the range of resulting bio-diesel costs is $0.72 to $1.21/L of diesel equivalent (2012$).

Converting to 2013$ and to a gge basis, the resulting cost range for FAME is $2.41–$4.03/gge. As with HRD and the pyrolysis fuels, a distribution and dispensing cost of $0.22/gge was included to derive a total cost range for B100 FAME diesel of $2.63–$4.25/gge, with an average cost of $3.25/gge.

Based on the $3.25/gge cost for 100% FAME diesel and the cost of $2.60/gge for conventional low-sulfur diesel (based on AEO 2015 data as described in Section 5.2), the resulting cost of a B20 blend of FAME is $2.72/gge.

5.4.3 Gas-To-Liquid Fischer-Tropsch Diesel (GTL FTD) Pathway

The C2G study includes a 100% GTL diesel pathway based on the Fischer-Tropsch processing of NG. Costs for this fuel pathway were based on Shuster et al. (2013), which modeled a mature technology plant configured to produce 50,000 barrels per day of GTL fuel.

Based on the report data and converting to 2013$ and $/gge basis, GTL fuel production costs are estimated to be $3.72/gge at the plant gate in 2025 ($2.81/gge in 2015). Including an additional $0.42/gge for distribution and dispensing (from the 2013 IEA report), the dispensed cost of GTL diesel in 2025 is estimated to be $4.14/gge.

5.5 ETHANOL (E85) FROM CORN STOVER

This C2G study investigates an ethanol (E85) from corn stover pathway as part of the FUTURE TECHNOLOGY case analysis.[9] We assume that the E85 pathway is actually 83% neat ethanol (100% ethanol) mixed with 17% gasoline blendstock, by volume, based on the high end of the ASTM D5798 range (ASTM 2015). To develop ethanol costs, the C2G study relies on publicly available DOE-supported R&D, design cases, and economic evaluations (Humbird et al. 2011; Tao et al. 2014). Model parameters were revised to reflect consistent C2G financial assumptions, described in Section 5.1. In addition to these financial parameters, this study relied on data from a variety of public sources to develop key input parameters to the TEA model, including feedstock cost, feedstock yield, capital investment, capacity utilization, and a project contingency factor for the ethanol facility construction.[10]

For the corn stover E85 cost estimation, feedstock costs were assumed to be $80/dry short ton (in 2011$), which is consistent with the assumptions used in the BETO MYPP (DOE 2014b). Facility capacity utilization (on-stream factor) was assumed to be 90%, consistent with the recent BETO-supported hydrocarbon pathways design cases (Davis 2013), as well as USDA reporting on the capacity utilization of starch-based ethanol plants (USDA 2015).

Midpoint ethanol costs as well as a low-high cost range were developed based on varying assumptions for ethanol process yield, with yield expressed in gallons of ethanol per dry ton of feedstock. The highest cost yield assumption (lowest yield) is based on the 2012 NREL state-of-technology pilot-scale demonstration, which had a yield of 71 gal/dry ton of feedstock (Tao et al. 2014). The baseline or midpoint yield estimate was based on the Abengoa Bioenergy corn stover biorefinery project in Kansas, which had a yield of 75 gal/dry ton (Globe 2010; DOE 2014a). Although the basis of the design case and demonstration efforts utilizes a bacteria, *Zymomonas mobilis*, the highest yield assumed (for the low cost case), is based on an 85% theoretical conversion efficiency, which is the highest practical conversion efficiency expected, considering carbohydrate use for yeast growth (Borglum 1980).

Cost ranges depend on the yield assumed for the process. The highest cost assumes a yield case is based on the 2012 NREL state-of-technology pilot-scale demonstration for ethanol production, the midpoint cost is based on currently publically reported Abengoa yields in their cellulosic bio-refinery, and the lowest cost assumed a yield in line with 85% theoretical conversion of sugars to ethanol (a potential stretch goal identified by the BETO program). The low-cost 85% efficiency yield is 93.5 gal/dry ton of feedstock.

In addition to the range of yield assumptions, the ethanol cost range was based on a range of assumptions for capital expenditures for the production plant. Plant capital was estimated using a capital expenditure ratio, estimating capital costs on a dollar per installed annual capacity basis ($/gal of annual capacity). Based on industrial feedback, the capital expenditure ratio was adjusted to meet a range of $10–12/gal of annual ethanol for the cost analysis. This adjustment was made based on industry feedback that suggested that n^{th} plant economics may not be applicable to corn stover E85 technologies by 2025. An additional 30% of capital costs was included as a contingency factor for the cases studied.

Based on the TEA modeling using the C2G input parameters discussed above, the baseline cost of ethanol (based on the Abengoa plant yield) was estimated to be $4.83/gge of pure E100. The low-high cost range of E100 was found to be $4.16–$5.08/gge. These neat ethanol costs were converted to E85 costs

---

[9] The CURRENT TECHNOLOGY case considers E85 from corn ethanol using costs from AEO 2015, as noted in Section 5.2.

[10] Since the 2025 FUTURE TECHNOLOGY cost projection is based on C2G financial assumptions and input parameters derived from public sources using C2G study team judgment and input from industrial stakeholders, ethanol costs in this study do not match DOE's MYPP or the NREL design reports.

(assuming a mix of 83% ethanol and 17% gasoline) using AEO 2015 data for the cost of gasoline blendstock. As the TEA modeling of costs was for production only, a $0.45/gge distribution and dispensing cost was added based on the 2013 IEA alternative fuels study. The final resulting dispensed cost was $4.69/gge for E85, with a range of $4.18/gge to $4.88/gge.

Figure 10 shows a cost range for ethanol produced from corn stover in a CURRENT TECHNOLOGY, LOW VOLUME case. This range is based on two cost estimates. The lower value, $5.06/gge of E85 with transport, corresponds to an estimate of $3.55/gal of E100 (2012$) reported in BNEF (2013), which surveyed 11 companies considered knowledgeable on cellulosic ethanol. Based on feedback from the C2G industrial partners and utilizing a recent report for cellulosic conversion facilities, a higher capital expenditure ratio of $18–22/gal annual ethanol capacity was incorporated in the NREL design case (Bomgardner 2013). Based on an ethanol yield of 71 gal/dry ton of feedstock and accounting for distribution, this capital expenditure range yields an average E85 cost of $6.73/gge.

5.6 ELECTRICITY

Electricity used as an upstream energy source is assumed to be average grid electricity based on AEO 2015 data. Similarly, electricity for electric vehicles and production of hydrogen fuel in the CURRENT TECHNOLOGY case is based on AEO 2015 price data for the average U.S. grid mix. In particular, CURRENT TECHNOLOGY case electricity is based on the AEO 2015 reference case average residential electricity price for 2015. AEO price data in 2013$/MMBtu were converted to $/gge using a conversion factor of 3,412.14 Btu/kWh. The resulting 2015 cost of electricity for electric vehicles is $3.98/gge. The approach taken in this report is a pathway approach and does not include the cost of electricity backup or storage.

For the FUTURE TECHNOLOGY case, several advanced and renewable electricity generation pathways are investigated for charging electric vehicles.[11] Advanced electricity generation pathways include:

- NG ACC with and without CCS
- Solar PV electricity
- Wind electricity

The fuel cost basis for these generation pathways comes from an AEO 2015 report on the cost of new electricity generation (EIA 2015c). This EIA report only addresses the cost of generation for these pathways. To determine the final cost to consumers for electricity in the FUTURE TECHNOLOGY case pathways, data from AEO 2015 on electricity pricing was used to estimate the final markup to the consumer (end user markup equals average electricity price to the residential consumer less the average cost of generation). All prices were converted to 2013$, and those values in $/kWh were converted to $/gge. See Table 32 for the resulting $/gge BEV fuel costs.

5.7 HYDROGEN FUEL

The C2G study investigates a number of H_2 fuel pathways for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY case analyses. For all pathways evaluated, H_2 is produced at a central facility and delivered to refueling stations via pressurized gas tube trailers. Hydrogen is dispensed to FCEVs at a pressure of 700 bar. The various H_2 pathways investigated vary based on the production technology used.

[11] This section describes the cost of electricity as a transportation fuel on a $/gge basis. While BEVs will use only electricity as a fuel, PHEVs will use both electricity and gasoline based on an assumed utility factor. This specialized case of fuel costing for PHEVs is covered in Section 9 as part of the LCD evaluation.

Table 32. AEO 2015 electricity price inputs and BEV fuel costs for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases[a]

Electricity Pathway	Generation Cost ($/kWh)	Distribution and Markup ($/kWh)	Final Price to Consumer ($/kWh)	Electric Vehicle Fuel Cost ($/gge)
CURRENT TECHNOLOGY case (2015)				
Average AEO 2015 grid mix	0.065	0.056	0.121	3.98
FUTURE TECHNOLOGY case (2025)				
NG ACC with CCS	0.10	0.065	0.165	5.43
NG ACC without CCS	0.073	0.065	0.138	4.52
Wind	0.074	0.065	0.139	4.56
Solar PV	0.114	0.065	0.179	5.90

[a] Cost data is expressed in 2013$.

To develop dispensed H_2 fuel costs, this study relies on two publicly available TEA models developed for DOE to estimate the levelized cost of H_2 production, delivery, and dispensing: H2A Production and HDSAM. The H2A model is actually a set of discounted cash flow, rate-of-return analysis tools (for both CURRENT TECHNOLOGY and FUTURE TECHNOLOGY case analysis) and associated case studies, which determine the levelized cost of H_2 production based on financial input parameters and cost and production process parameters, such as capital cost, feedstock usage and cost, process efficiency, capacity utilization, and operations and maintenance costs. Similarly, the HDSAM is a discounted cash flow, rate-of-return analysis tool that can evaluate a wide variety of H_2 delivery and dispensing scenarios (including delivery and dispensing pathways, geographical locations, and FCEV penetration rates) and determine the levelized cost of H_2 delivery and dispensing based on energy use and cost, system and station capital costs, capacity utilization, operating and maintenance costs, etc.

As with the pyrolysis fuel and ethanol pathways, the H2A and HDSAM model parameters were revised to reflect consistent C2G financial assumptions across pathways, as described in Section 5.1. In addition to the financial parameters, the C2G study used data from public sources for pricing of feedstock and energy sources used, primarily the BETO MYPP for woody biomass feedstock costs and AEO 2015 for most other energy costs (e.g., NG, gasoline and diesel, grid electricity). Wind electricity cost (used only in the wind electrolysis production pathway) was based on the AEO 2015 new electricity generation report discussed in Section 5.5 (EIA 2015a).

The C2G study investigated the following H_2 fuel pathways:

- CURRENT TECHNOLOGY case: NG reformation (with no CCS)
- FUTURE TECHNOLOGY case:
  - NG reformation (with CCS)
  - Woody biomass gasification
  - Water electrolysis (alkaline technology) using wind electricity.

Hydrogen production costs for these pathways were based on the corresponding H2A (V 3.0) current and future case studies, with input and feedstock cost parameters revised as discussed above (DOE 2015c). Delivery and dispensing costs for delivery by truck and refueling station dispensing at 700 bar were

developed using the current and future technology HDSAM (V 2.0) and AEO 2014 price inputs (DOE 2015b; EIA 2014a).

Based on the C2G modeling of the H_2 pathways, delivery and dispensing costs are $3.60/gge for the CURRENT TECHNOLOGY, HIGH VOLUME case and $2.59/gge for the FUTURE TECHNOLOGY, HIGH VOLUME case. Production costs for the CURRENT TECHNOLOGY, HIGH VOLUME case are $1.30/gge for the NG reformation pathway. Production costs for the FUTURE TECHNOLOGY, HIGH VOLUME case are $2.00/gge for the NG reformation with CCS pathway, $2.19/gge for the biomass gasification case, and $4.82/gge for the grid electrolysis case. Based on these delivery and production costs, total dispensed cost for the CURRENT TECHNOLOGY, HIGH VOLUME case is $4.90/gge for the NG reformation pathway. Total dispensed costs for the FUTURE TECHNOLOGY, HIGH VOLUME case are $4.59/gge for the NG reformation with CCS pathway, $4.78/gge for the biomass gasification case, and $7.41/gge for the grid electrolysis case. See Table 33.

Table 33. Hydrogen pathway costs for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases (2013$)

Hydrogen Pathway	Production Cost ($/gge)	Delivery and Dispensing Cost ($/gge)	Total Dispensed H_2 Cost ($/gge)
CURRENT TECHNOLOGY case (2015)			
NG reformation	1.30	3.60	4.90
LOW-VOLUME Case (SMR)	1.30	7.80	9.10
FUTURE TECHNOLOGY case (2025)			
NG reformation with CCS	2.00	2.59	4.59
Biomass gasification	2.19	2.59	4.78
Wind electrolysis	4.82	2.59	7.41

As H_2 fuel for FCEVs is only beginning to emerge as a commercially available transportation fuel, a CURRENT TECHNOLOGY, LOW VOLUME case was evaluated to better estimate the cost of H_2 in the near term and to understand how such fuel costs affect the LCD for FCEVs in this timeframe. To develop the low-volume H_2 fuel cost, a scenario based on 10,000 FCEVs in the southern California region was evaluated. Data from NPC (2012) was used to estimate H_2 station cost and size and the number of stations needed to support these FCEVs. Using these cost and scenario assumptions, H2A and HDSAM modeling was used to develop the CURRENT TECHNOLOGY, LOW VOLUME cost estimate of $9.10/gge of H_2.

5.8 REFERENCES FOR SECTION 5

API (American Petroleum Institute), 2014. *Gasoline Tax*. http://www.api.org/oil-and-natural-gas-overview/industry-economics/fuel-taxes/gasoline-tax

ASTM (American Society for Testing and Materials) International, 2015. *ASTM D5798-15, Standard Specification for Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines*. ASTM International, West Conshohocken, PA. http://www.astm.org/Standards/D5798.htm

BEA (Bureau of Economic Analysis), U.S. Department of Commerce, 2015. *National Income and Produce Account Tables*. http://www.bea.gov/iTable/iTableHtml.cfm?reqid=9&step=3&isuri=1&903=13

BNEF (Bloomberg New Energy Finance), 2013. *Cellulosic Ethanol Heads for Cost-Competitiveness by 2016*. http://about.bnef.com/press-releases/cellulosic-ethanol-heads-for-cost-competitiveness-by-2016/

Bomgardner, M.M., 2013. "Building a New Biofuels Industry." *Chemical & Engineering News*, Vol. 91, Issue 4: 20–22. http://cen.acs.org/articles/91/i4/Building-New-Biofuels-Industry.html

Borglum, G.B., 1980. *Starch Hydrolysis for Ethanol Production*. https://web.anl.gov/PCS/acsfuel/preprint%20archive/Files/25_4_SAN%20FRANCISCO_08-80_0264.pdf

Cazzola, P., G. Morrison, H. Kaneko, F. Cuenot, A. Ghandi, and L. Fulton, 2013. *Production Costs of Alternative Transportation Fuels*. International Energy Agency, Paris, France. http://www.iea.org/publications/freepublications/publication/production-costs-of-alternative-transportation-fuels-influence-of-crude-oil-price-and-technology-maturity-.html

Davis, R., Tao, L., Tan, E.C.D., Biddy, M.J., Beckham, G.T., Scarlata, C., Jacobson, J., Cafferty, K., Ross, J., Lukas, J., Knorr, D., and Schoen, P., 2013. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*. Report TP-5100-60223, NREL. http://www.nrel.gov/docs/fy14osti/60223.pdf

DOE (U.S. Department of Energy), 2014a. *Abengoa*. http://www.energy.gov/eere/bioenergy/abengoa

DOE, 2014b. *Bioenergy Technologies Office Multi-Year Program Plan*, July. http://www.energy.gov/sites/prod/files/2014/07/f17/mypp_july_2014.pdf

DOE, Hydrogen and Fuel Cells Program, 2015b. *DOE H2A Delivery Analysis*. https://www.hydrogen.energy.gov/h2a_delivery.html

DOE, Hydrogen and Fuel Cells Program, 2015c. *DOE H2A Production Analysis*. https://www.hydrogen.energy.gov/h2a_production.html

EIA (U.S. Energy Information Administration), 2014a. *Annual Energy Outlook 2014 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf

EIA, 2015a. *Annual Energy Outlook 2015 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

EIA, 2015b. *Assumptions to the Annual Energy Outlook 2015*. http://www.eia.gov/forecasts/aeo/assumptions/pdf/liquidfuels.pdf

EIA, 2015c. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015*. https://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

Globe Newswire, 2010. *Abengoa Bioenergy and Mid-Kansas Electric Reach Agreement Concerning First Commercial-Scale Hybrid Cellulosic Ethanol and Power Plant in U.S.* January 19. http://www.globenewswire.com/news-release/2010/01/19/412515/182207/en/Abengoa-Bioenergy-and-Mid-Kansas-Electric-Reach-Agreement-Concerning-First-Commercial-Scale-Hybrid-Cellulosic-Ethanol-and-Power-Plant-in-U-S.html

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., and Dudgeon, D., 2011. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*. Report TP-5100-47764, NREL. http://www.nrel.gov/docs/fy11osti/47764.pdf

IRENA (International Renewable Energy Agency), 2013. *Road Transport: The Cost of Renewable Solutions.* IRENA Innovation and Technology Centre, Bonn, Germany. http://www.irena.org/DocumentDownloads/Publications/Road_Transport.pdf

Jones, S.B., P.A. Meyer, L.J. Snowden-Swan, A.B. Padmaperuma, E. Tan, A. Dutta, J. Jacobson, and K. Cafferty, 2013. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway*. Report PNNL-23053 / NREL/TP-5100-61178, Pacific Northwest National Laboratory, Richland, WA. http://www.nrel.gov/docs/fy14osti/61178.pdf

Jones, S.B., L.J. Snowden-Swan, P.A. Meyer, A.H. Zacher, M.V. Olarte, and C. Drennan, 2014. *Fast Pyrolysis and Hydrotreating: 2013 State of Technology R&D and Projections to 2017*, Report PNNL-23294, Pacific Northwest National Laboratory, Richland, WA. http://dx.doi.org/10.2172/1149669

NPC (National Petroleum Council), 2012. *Advancing Technology for America's Transportation*. http://www.npc.org/reports/trans.html

Pearlson, M., Wollersheim, C., and Hileman, J., 2013. "A Techno-economic Review of Hydroprocessed Renewable Esters and Fatty Acids for Jet Fuel Production," *Biofuels, Bio-Products, & Bio-Refining*, 7:89–96, John Wiley & Sons. http://dx.doi.org/10.1002/bbb.1378

Shuster, E., et al., 2013. *Analysis of Natural Gas-to-Liquid Transportation Fuels via Fischer-Tropsch*. Report DOE/NETL-2013/1597, National Energy Technology Laboratory. http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Gas-to-Liquids_Report.pdf

Tao L., D. Schell, R. Davis, E. Tan, R. Elander, and A. Bratis, 2014. *NREL 2012 Achievement of Ethanol Cost Targets: Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*. Report NREL/TP-5100-61563. http://www.nrel.gov/docs/fy14osti/61563.pdf

USDA (U.S. Department of Agriculture), Economic Research Service, 2015. *U.S. Bioenergy Statistics*. http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx

6 VEHICLE FUEL CONSUMPTION AND COST ASSUMPTIONS

6.1 AUTONOMIE SUMMARY

Vehicle fuel consumption and vehicle technology cost are critical inputs to estimate the C2G energy use, GHG emissions, and LCD for each vehicle-fuel combination. The calculation of fuel consumption and cost of vehicle technologies requires an automotive control-system design and simulation tool. This study used Autonomie, a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. Autonomie, developed by Argonne in collaboration with General Motors, is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (e.g., calibration, validation). Several Autonomie powertrain models with varying vehicle classes have been validated using Argonne's Advanced Powertrain Research Facility vehicle test data (Cao et al. 2007; Kim et al. 2009; Pasquier et al. 2001; Rousseau 2000; Rousseau et al. 2006).

To evaluate the fuel consumption and cost of a given vehicle architecture (ICEV, FCV, HEV, PHEV, and BEV), a vehicle model is built from the ground up based on data for each component in the main Autonomie database. The vehicle components are sized by internal algorithms to meet the same vehicle technical specification, as given in Section 6.2. With the resulting vehicle component sizes determined, the vehicle cost is then estimated from the cost of the components. Finally, the fuel consumption is simulated on the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET) cycles. The assumptions and results described in this report are documented in detail in Moawad et al. (2016). A comparison of the vehicle cost and fuel economy of the modeled vehicles and commercially available vehicles is presented in Appendix B.

Autonomie is designed to assess vehicle technologies for five laboratory timeframes: 2010 (reference), 2015, 2020, 2030, and 2045. Laboratory year is assumed to precede market introduction by 5 years. Hence, 2010 laboratory technology and cost points would be expected to appear in the market in 2015. The reference laboratory 2010 and 2020 vehicles in Autonomie were selected as CURRENT TECHNOLOGY (MY2015) and FUTURE TECHNOLOGY (MY2025–2030) vehicles, respectively. For laboratory years 2015 and beyond, uncertainties in both component performance and in component cost are taken into account by considering three different progress levels for both technology performance and technology cost: low, medium, and high. The low-, medium-, and high-progress cases are defined to represent, respectively, the 90th percentile, 50th percentile, and 10th percentile probability outcomes. For technology progress, the 90th percentile is the low-progress level where the technology has a 90% chance of being available at the time considered. The 10th percentile is the high-progress level where the technology has a 10% chance of being available at the time considered. The high-progress (10% probability) technical and cost progress assumptions in the Autonomie model are based on the U.S. DRIVE program goals where available. Assumptions used for the low- and medium-progress levels for technology and costs in the Autonomie model were developed through discussions with experts from companies, universities, and the national laboratories. Low, medium, and high progress in reducing component cost leads to high, medium, and low component costs, respectively. To avoid confusion, we opted to refer to possible FUTURE TECHNOLOGY cost outcomes as either low cost, medium cost, or high cost.

For each vehicle considered, the performance and cost follow a triangular uncertainty distribution. Assumptions of technology progress affect component costs within the model (but assumptions of component costs progress do not affect technology progress). As an example, high technical progress in lightweighting the glider leads to an increased cost of the glider, reflecting use of more expensive, lighter-weight materials. The lighter-weight glider can enable substantial powertrain cost savings for some vehicle technologies (e.g., smaller battery required for BEVs). For total vehicle costs, the output of the

Autonomie model is a 3×3 matrix for the 9 possible combinations of low, medium, and high progress in technology performance and low, medium, and high technology cost. Intuitively, it seems likely that there will be a correlation between improvements in component performance and improvements in component cost; however, the degree of correlation is difficult to assess. To simplify the analysis in this study, we opted to consider Autonomie results for medium technology progress with low, medium, and high component costs. This simplification allows an assessment of the sensitivity of driving costs and CO_2 abatement costs to the cost assumptions for a given vehicle. Unless noted otherwise, all data in this report were derived using the medium vehicle technology progress assumptions in Moawad et al. (2016).

Autonomie includes the following vehicle classes, powertrain configurations, and fuel options:

- Five powertrain configurations: ICEV, HEV, PHEV, FCEV, BEV
- Four fuels for ICEs: gasoline, diesel, E85, and CNG
- Five vehicle classes: compact car, midsize car, small SUV, medium SUV, and pickup truck.

The fuel economy results for gasoline, diesel, and CNG vehicles for Autonomie were used in this study, and it was assumed that E85 and LPG vehicles have the same energy consumption (LHV basis) as gasoline vehicles. For HEV and PHEV10, a power-split configuration is used, while a series configuration is used for FCEV and PHEV35. In the case of a fuel-cell system, the electrical energy is directly used by the electric machine.

Fuel-cell vehicles are undergoing extensive R&D because of their potential for high efficiency and low emissions (zero emission). The peak fuel cell efficiency is assumed to be at 59% for the CURRENT TECHNOLOGY case and is assumed to increase to 65% for the FUTURE TECHNOLOGY case (see Figure 27 in Moawad et al. 2016). These efficiencies are substantially higher than for gasoline ICEVs (assumed to be 36% and 42% for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, respectively (see Figure 23 in Moawad et al. 2016). The fuel cell system model used for this study was based on a steady-state look-up table. The fuel cell system map (5x mass activity) was provided by Argonne's fuel cell group using GCTool (Argonne 2015).

The PHEV35, BEV90, and BEV210 vehicles in this study were taken from, and are identical to, the vehicles labeled PHEV40, BEV100, and BEV300 in the Autonomie model (Moawad et al. 2016). For details on the different nomenclature used in the two studies see Section 3.2.

6.2 VEHICLE COMPONENTS SIZING

Vehicle components are sized through an iterative process to meet the following vehicle technical specifications:

- Initial vehicle movement to 60 mph in 9 sec ±0.1 sec,
- Maximum grade of 6% at 65 mph at GVW, and
- Maximum vehicle speed >100 mph.

In addition to the vehicle technical specifications, the following additional rules are applied to electric vehicles:

- For HEVs, the electric-machine and battery powers were determined to enable capture of the regenerative braking energy during a UDDS cycle. The engine and the generator were then sized to meet the gradeability and performance requirements.
- For PHEV10s, the electric-machine and battery powers were sized to be able to follow the UDDS cycle in electric-only mode (this control was only used for the sizing; a blended approach was used to evaluate the consumption of gasoline and electricity). The battery-usable energy was

chosen to allow the vehicle to follow the UDDS drive cycle for 10 mi in electric-only mode. The engine was then sized to meet both performance and gradeability requirements (usually gradeability is the determining factor for PHEVs).

- For PHEV35s, the main electric-machine and battery powers were sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode. The battery-usable energy was defined to follow the UDDS drive cycle for 40 mi at battery EOL.[12] The engine and generator set or the fuel-cell systems were sized to meet the gradeability requirements.
- For H_2 FCEVs, the hydrogen storage system is sized to yield a driving range of 320 mi.

6.3 FUEL ECONOMY AND ELECTRICITY CONSUMPTION

Tables 34 and 35 list the Autonomie simulations of fuel economy and electricity consumption per vehicle mile travelled (VMT) over the UDDS and HWFET driving cycles (and the corresponding on-road adjusted results). Note that the electricity consumption by plug-in vehicles (BEVs and PHEVs) is from battery to wheels, excluding the battery charging efficiency. A battery charging efficiency (85% for CURRENT TECHNOLOGY and 88% for FUTURE TECHNOLOGY) is applied to calculate electricity consumption at wall outlets. Laboratory fuel economy testing is conducted under much milder conditions than "real-world" driving, with maximum speed of 60 mph, mild climate conditions (75°F), mild acceleration rates, and no use of fuel-consuming accessories, such as air conditioning. To reflect the actual "on-road" fuel and electricity consumption that occurs during "real-world" driving, we apply mpg-based formulas developed by EPA to estimate the on-road fuel economy based on a five-cycle testing method from the laboratory test results (EPA 2006), as shown below.

$$\text{On-road city fuel economy} = 1/(0.003259 + 1.1805/\text{UDDS fuel economy})$$

$$\text{On-road highway fuel economy} = 1/(0.001376 + 1.3466/\text{HWFET fuel economy})$$

Note that the regression lines for these mpg-based formulas are based on test data for vehicles, the vast majority of which are gasoline ICEVs. Thus, the validity of extrapolating the mpg-based formulas to vehicles that offer much higher fuel economy (e.g., FCEVs and BEVs) is questionable. In this study, following the method described by Stephens et al. (2013) and Elgowainy et al. (2010), the adjustment factor is capped at 0.7, which is consistent with the suggested window-sticker calculation for the Mini-e demonstration electric vehicle (Weissler 2009). This is discussed in further detail in Section 3.2.

PHEVs have two operating modes: charge depleting (CD) and charge sustaining (CS) modes. During the CD mode, the vehicle uses electricity stored into its battery from previous charging at a wall outlet until the state-of-charge is depleted to a predetermined level. For the power-split PHEV10, the CD mode is a blended operation where ICE power is required for high-speed/load operations to assist the electric motor. For the EREV (PHEV35), the CD mode is all-electric. When the state-of-charge reaches a predetermined level, the vehicle switches to the CS mode where the vehicle operates like a regular HEV.

[12] A detailed discussion of the battery sizing and the corresponding driving range is presented in Section 3.2.

Table 34. Test cycle (lab) and on-road adjusted fuel economy and electricity consumption for gasoline, CNG, and diesel ICEVs; gasoline HEVs; H_2 FCEVs; and BEVs 90 and 210 (units are in the first column)

Vehicle and Test		Test Cycle		On-road Adjusted	
		CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
Gasoline SI ICEV (mpgge)	UDDS	29.6	40.3	23.2	30.7
	HWFET	42.3	56.3	30.1	39.5
CNG SI ICEV (mpgge)	UDDS	31.4	37.3	24.5	28.7
	HWFET	44.6	51.7	31.7	36.5
Diesel CI ICEV (mpgge)	UDDS	36.4	45.3	28.0	34.1
	HWFET	51.5	62.2	36.3	43.6 [a]
Gasoline SI HEV (mpgge)	UDDS	56.2	83.4	41.2	58.4
	HWFET	49.0	74.2	34.7	51.9 [a]
H_2 FCEV (mpgge)	UDDS	76.1	105.5	53.3[a]	73.8 [a]
	HWFET	81.0	104.6	56.7 [a]	73.2 [a]
BEV90 (Wh/mi)	UDDS	228	183	325 [a]	262 [a]
	HWFET	230	197	329 [a]	282 [a]
BEV210 (Wh/mi)	UDDS	282	213	403 [a]	304 [a]
	HWFET	264	216	377 [a]	309 [a]

[a] The adjustment factor is capped at 0.7.

Two sources of energy and two driving modes in PHEVs make on-road adjustment for PHEVs more uncertain than those for conventional vehicles. We follow the same procedure of on-road adjustment for PHEVs as used by Stephens et al. (2013) and Elgowainy et al. (2010). For both PHEV10 and PHEV35, the fuel economy in the CS mode is adjusted using the EPA mpg-based formulas with the adjustment factor capped at 0.7 because the mode of operation is similar to that of a regular HEV. For the CD mode of the PHEV10, we assume that the additional on-road load (compared with the test cycle load) would result in a fuel consumption increase rather than an electricity consumption increase. Also, the amount of the fuel consumption increase is assumed to be similar to the increase during CS operation by the same vehicle for the same additional load. In other words, on-road electricity consumption in CD mode remains the same as the corresponding test-cycle electricity consumption, while the laboratory fuel consumption in CD mode for power-split PHEVs was adjusted by the same increase in fuel consumption associated with the CS operation of the same vehicle. For the CD mode of the PHEV35, we adjusted fuel and electricity consumption by a factor of 0.7 since the on-road load is mostly met by the battery power, with minor assistance from the engine. Detailed discussion of the on-road adjustment is provided in Stephens et al. (2013) and Elgowainy et al. (2010).

Note that there is a small difference (≈2%) in the gasoline LHVs assumed in the Autonomie (114,453 Btu/gal) and GREET (112,194 Btu/gal) models. To account for this difference, the mpgge results are multiplied by the ratio of the gasoline LHVs in the GREET and Autonomie models. With this gasoline property adjustment, the fuel consumption in Btu/mi is consistent between the GREET and Autonomie models. Finally, the combined fuel economy and electricity consumption are calculated as a weighted average of UDDS (43%) and HWFET (57%) results. Note that EPA applies the 43/57 split with

Table 35. Autonomie-modeled test cycle and on-road adjusted fuel economy and electricity consumption for the gasoline PHEV10 and PHEV35

Vehicle and Test		Mode and Units	Test Cycle		On-road Adjusted	
			CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
PHEV10 (power-split)	UDDS	CD electric (Wh/mi)	215	177	215	177
		CD engine (Btu/mi) [a]	244	121	994	722
		CS engine (mpgge)	55	82	40	57 [b]
	HWFET	CD electric (Wh/mi)	229	222	229	222
		CD engine (Btu/mi) [a]	251	28	1,230	706
		CS engine (mpgge)	48	72	34	51 [b]
PHEV35 (EREV)	UDDS	CD electric (Wh/mi)	226	174	323	249
		CS engine (mpgge)	48	77	36	54
	HWFET	CD electric (Wh/mi)	249	205	356	293
		CS engine (mpgge)	50	73	35	51

[a] The PHEV10 has a power-split configuration and a small amount of gasoline is used in the CD mode; the total energy consumption in CD mode can be computed by adding the electricity and gasoline use.

[b] The adjustment factor in EPA mpg-based formulas is capped at 0.7.

respect to the mpg-based fuel economy values, while the 55/45 split is applied for the (unadjusted) test-cycle fuel economy values (EPA 2006). EPA (2015b) assumed the 55% city/45% highway weighting gradually changed to a 43% city/57% highway weighting in a linear fashion over the period 1986 to 2005.

We adopted a harmonic average weighting of 43% city/57% highway fuel economies because it correlated with the driving activity studies underlying the 5-cycle methodology and mpg-based formula as reported in EPA (2015b).

Table 36 summarizes the combined fuel economy and electricity consumption adjusted for on-road performance. The right two columns express the combined fuel economy as ratios relative to gasoline SI ICEVs. The CD distance of PHEVs 10 and 35 is calculated from the CD electricity consumption and the usable battery energy estimated by Autonomie. As mentioned earlier, the mpgge fuel economy ratios for E85 and LPG ICEVs were assumed to be the same as for gasoline ICEVs. Figure 11 presents the fuel economy ratios relative to the CURRENT TECHNOLOGY gasoline ICEVs.

Note that the CURRENT TECHNOLOGY ICEV fuel economy was based on a conventional engine efficiency map. Our baseline vehicle is a midsize conventional vehicle with a naturally aspirated inline four-cylinder engine with variable valve timing, a 6-speed automatic transmission, and vehicle characteristics averaged over the entire midsize fleet (aerodynamic coefficients, rolling resistance, glider mass, etc.). However, other advanced engine technologies can achieve improved fuel economies compared to the conventional ICEV at incremental cost. This analysis did not consider specific technology pathways to improve the ICEV or pathways for ICEV improvement in the CURRENT TECHNOLOGY set. As an example, the authors point to a representative set of cost/GHG emissions data for various technologies that improve the efficiency of a midsize ICE vehicle is available in the EPA/NHTSA rule-making studies (GPO 2012). Additionally, Appendix B addresses the comparison of fuel economy and cost of the modeled vehicles from this report with MY2015 midsize cars sold in the retail market.

Table 36. Combined fuel economy and electricity consumption adjusted for on-road performance

Vehicle, Mode, and Unit	Fuel Economy Adjusted for On-road Performance [a]		Fuel Economy Ratio (relative to baseline gasoline ICEV) (%)	
	CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
Gasoline SI ICEV (mpgge)	26.2	34.5	100	100
E85 SI ICEV (mpgge) [b]	26.2	36.2	100	105
CNG SI ICEV (mpgge)	27.6	32.0	105	93
LPG SI ICEV (mpgge) [b]	26.2	34.5	100	100
Diesel CI ICEV (mpgge)	31.6	38.1	121	111
Gasoline SI HEV (mpgge)	36.5	53.5	139	155
H_2 FCEV (mpgge)	54.1	72.0	207	209
BEV90 (mpgge)	100.5	120.4	384	349
BEV210 (mpgge)	84.6	107.3	324	311
PHEV10 (power-split				
CD electricity consumption (Wh/mi)	223	203		
CD fuel consumption (Btu/mi)	1,129	713		
CD distance (mi)	12	10		
CS fuel economy (mpgge)	35.8	52.2	137	151
CD fuel economy (mpgge)	59.4	79.9	227	232
PHEV35 (EREV)				
CD electricity consumption (Wh/mi)	342	274		
CD fuel consumption (Btu/mi)	2	2		
CD distance (mi)	35	33		
CS fuel economy (mpgge)	34.8	51.1	133	148
CD fuel economy (mpgge)	95.9	119.6	366	347

[a] Units are given in the first column.

[b] Assumed equal to gasoline ICEV. The efficiency of CURRENT TECHNOLOGY and FUTURE TECHNOLOGY vehicles was computed assuming medium technology progress.

6.4 VEHICLE WEIGHT AND COMPOSITION

The vehicle weight and composition results are essential for estimating the energy use and emissions associated with the vehicle manufacturing cycle. We obtained mass estimates for 7 major vehicle components (glider, engine, fuel cell, transmission, energy storage, motor, and wheels) from Autonomie. In GREET, glider, engine, fuel cell, transmission, energy storage, motor, and wheels are categorized into glider, powertrain, powertrain, transmission, battery, traction motor and other electric machines/control, and wheels, respectively (Argonne 2014). The other components include 12-V battery, fuel tanks, exhaust, etc. The mass of the 12-V battery is based on the GREET default battery assumptions (36 lb for gasoline, E85, CNG, and diesel ICEVs and 22 lb for gasoline HEVs, gasoline PHEVs, BEVs, and FCEVs). The balance of total vehicle mass and the sum of major components mass and 12-V battery is added to the powertrain for gasoline, E85, CNG, and diesel ICEVs, gasoline HEVs, gasoline PHEVs, and FCEVs assuming the majority of the remaining mass is fuel tanks and exhaust for these vehicle types, and to the motor for BEVs assuming the majority of the remaining mass is electric machines and controls.

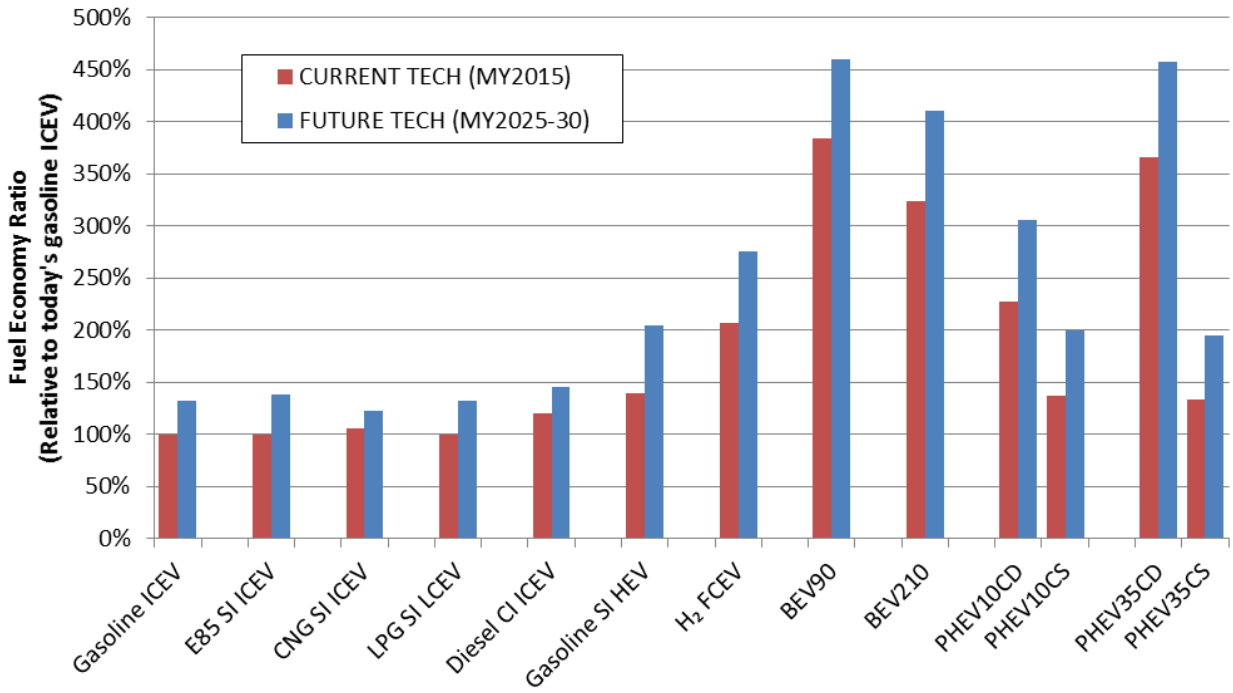

Figure 11. Vehicle fuel economy (mpgge) ratio relative to CURRENT TECHNOLOGY gasoline ICEV assuming medium technology progress

Figure 12 and Table 37 summarize the weight of components for the different vehicles. It was assumed that the components of the LPG ICEV had the same weight as those for the gasoline ICEV. As seen in Figure 12, for all vehicles except the CURRENT TECHNOLOGY BEV210, the glider mass accounts for the majority of the vehicle mass. The battery mass in the CURRENT TECHNOLOGY BEV210 is 1,314 lb (4,268 × 0.308, see Table 37). This mass is consistent with that in actual vehicles currently on the road.

Vehicle weight decreases by 14% and 28% between the CURRENT TECHNOLOGY (MY2015) and FUTURE TECHNOLOGY (MY2025–2030) cases. As shown in Figure 12, different weight reductions are expected for different vehicle powertrains. The weight reduction for the gasoline ICEV, E85 ICEV, CNG ICEV, and diesel ICEV are in the range 14–17%; the weight reduction for the HEVs and PHEVs are 17–23%; and the FCEV has a 20% weight reduction. The weights of the BEV90 and BEV210 decrease by 23% and 28%, respectively. Overall, significant weight reductions can be achieved compared with current technologies, especially for vehicles with large batteries because the battery weight reduction is the most noticeable among the components—ranging from 32% to 54%. The other components with a large weight reduction include a traction motor (20–31%) and glider (21%).

The high-power energy storage of HEVs, FCEVs, BEVs, and PHEVs is assumed to be a Li-ion battery. The 12-V battery is a lead-acid battery. It is assumed that the Li-ion battery is not replaced during the vehicle lifetime, while the lead-acid battery is replaced twice. Tires are assumed to be replaced three times during the vehicle lifetime. All vehicles except the BEV90 are assumed to travel 178,102 mi during their lifetime; the BEV90 is assumed to travel 124,671 mi.[13]

[13] The lifetime mileages come from the NHTSA and Idaho National Laboratory (NHTSA 2006; Francfort 2015). A detailed discussion of these mileages is given in Section 9.

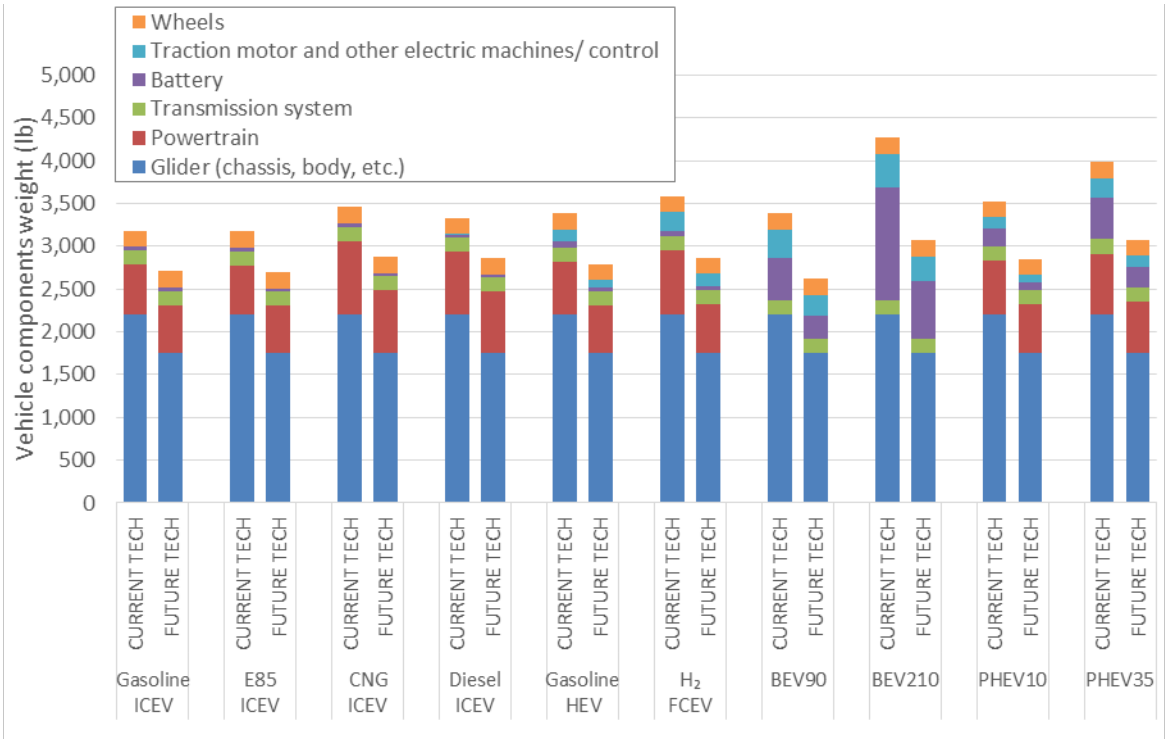

Figure 12. Vehicle component weight results (lb)

6.4.1 Advanced Battery Cost Assumptions

The cost assumptions in this C2G report are aligned with the goals of U.S. DRIVE battery R&D, which intends to develop the technologies that will reduce battery costs to $125/kWh. The main cost drivers of high-energy Li-ion batteries are the high cost of raw materials and materials processing, the cost of cell and module packaging, and manufacturing costs. Addressing the cost barrier requires developing and evaluating lower-cost components, including much higher-energy active materials, alternate packaging, and processing methods, and working jointly with U.S. suppliers to implement these low-cost solutions. Higher-energy and higher-power electrode materials promise to significantly lower battery cost by reducing the amount of material and the number of cells needed for the entire battery pack. Work is needed to develop new materials and electrode couples that offer a significant improvement.

In addition, current battery technology is very far from its theoretical energy density limit. In the near term (2016–2022), with advances in Li-ion technology, it may be possible to more than double the battery pack energy density from 100 Wh/kg to 250 Wh/kg with new high-capacity cathodes, higher-voltage electrolytes, and high-capacity silicon- or tin-based intermetallic alloys to replace graphite anodes. Specific near-term opportunities for increasing energy density include using silicon anodes with advanced cathodes and improvements in pack efficiency by removing redundant components/materials. Despite current advances, much more R&D will be needed to achieve the performance and lifetime requirements for deployment of these advanced technologies. Some specific technologies of interest include, but are not limited to, the design and development of second-generation Li-ion batteries that contain high-voltage (5-V) cathode materials and capacity of 200–250 mAh/g; the design and development of third-generation Li-ion batteries that contain advanced metal alloy and composite anodes, such as silicon carbon that offer two to four times the capacity of today's graphite anodes; and high-voltage, solid polymer composite electrolytes (currently at TRLs 3 and 4). Also, efforts must include the development of novel electrolyte formulations and additives to form a stable solid electrolyte interphase for improved abuse tolerance, longer life, low-temperature operation, and fast charge capability (also at TRLs 3 and 4).

Table 37. Vehicle weight and composition results

CURRENT TECHNOLOGY	Gasoline ICEV	E85 ICEV	CNG ICEV	Diesel ICEV	Gasoline HEV	H_2 FCEV	BEV90	BEV210	PHEV10	PHEV35
Vehicle weight	3,183 lb	3,170 lb	3,457 lb	3,331 lb	3,380 lb	3,587 lb	3,384 lb	4,268 lb	3,527 lb	3,982 lb
Weight composition										
Glider	69.3%	69.5%	63.8%	66.2%	65.2%	61.5%	65.1%	51.7%	62.5%	55.4%
Powertrain	18.4%	18.1%	24.9%	22.0%	18.3%	20.7%	0.0%	0.0%	17.9%	17.8%
Transmission	5.2%	5.2%	4.8%	5.0%	4.9%	4.6%	4.9%	3.9%	4.7%	4.2%
Battery	1.1%	1.1%	1.0%	1.1%	1.8%	2.0%	14.7%	30.8%	5.6%	12.2%
Traction motor and other electric machines/control	0%	0%	0%	0%	4.2%	6.1%	9.7%	9.3%	3.9%	5.7%
Wheels	5.9%	5.9%	5.4%	5.6%	5.5%	5.2%	5.5%	4.4%	5.3%	4.7%
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV**	**BEV90**	**BEV210**	**PHEV10**	**PHEV35**
Vehicle weight	2,705 lb	2,696 lb	2,875 lb	2,862 lb	2,791 lb	2,868 lb	2,621 lb	3,067 lb	2,851 lb	3,075 lb
Weight composition										
Glider	64.7%	64.9%	60.8%	61.1%	62.7%	61.0%	66.7%	57.0%	61.4%	56.9%
Powertrain	20.9%	20.6%	25.6%	25.2%	20.1%	20.0%	0.0%	0.0%	19.9%	19.8%
Transmission system	6.1%	6.1%	5.8%	5.8%	5.9%	5.8%	6.3%	5.4%	5.8%	5.4%
Battery	1.3%	1.3%	1.3%	1.3%	1.5%	1.6%	10.3%	22.3%	3.2%	7.7%
Traction motor and other electric machines/control	0%	0%	0%	0%	3.1%	5.1%	9.5%	9.2%	3.2%	4.2%
Wheels	6.9%	7.0%	6.5%	6.5%	6.7%	6.5%	7.1%	6.1%	6.6%	6.1%

In the longer term (2022–2027), "beyond Li-ion" battery chemistries, such as lithium-sulfur, magnesium-ion, zinc-air, and lithium-air (currently at TRLs 1–3), offer the possibility of energy densities that are significantly greater than those of current Li-ion batteries, as well as the potential for greatly reduced battery cost. However, major shortcomings in lifecycle, power density, energy efficiency, abuse tolerance, and manufacturing cost currently stand in the way of commercial introduction of state-of-the-art "beyond Li-ion" battery systems. Breakthrough innovations will be required for these new battery technologies to enter the electric vehicle market. Going forward, a larger portion of battery research will be on advanced battery technologies that offer the potential for very high energy and low cost, such as solid-state (lithium metal with solid electrolytes), lithium sulfur, and lithium air batteries (TRLs 1–3). These battery technologies promise high capacity (>300 mAh/g) and theoretical energy densities from two to five times that of traditional Li-ion. In addition, some non-lithium couples (e.g., magnesium, zinc) may show promise in the low-cost arena in the long term. Research is needed to advance these next-generation technologies from university and national laboratory R&D to the first stages of industry development through the development and testing of full cells.

Additional information on U.S. DRIVE battery R&D activities to reduce cost and increase energy density is detailed in the Electrochemical Energy Storage Technical Team Roadmap (U.S. DRIVE 2013).

6.5 VEHICLE COST

Autonomie provides estimates of total vehicle manufacturing costs at volume based on a summation of component costs plus the assembly costs (Moawad et al. 2016). All vehicle types are modeled using a constant set of performance parameters (acceleration time, top speed, gradeability, etc.). Technical progress, therefore, manifests itself as lower cost and/or improved fuel efficiency. For each vehicle type in each year, and for each degree of technical progress, three costs are estimated. This results in a 3×3 matrix for the 9 possible combinations of low, medium, and high progress in technology performance and low, medium, and high vehicle cost.

To simplify the analysis in this study, we opted to consider the Autonomie results for medium technology progress, using the low- and high-cost modeling results to develop a vehicle cost range for our analysis. Vehicle costs for the base case in our analysis were assumed to be the average of these low and high vehicle costs from the Autonomie medium technology progress case.

Table 38 shows the retail price equivalents (RPEs) for vehicles in this study. For all vehicles, the total cost is taken as the midpoint between the low and high manufacturing cost values given in Moawad et al. (2016) for a midsize car (assuming a medium degree of technical progress for the FUTURE TECHNOLOGY, HIGH VOLUME case). In Table 38, the incremental cost is relative to the conventional gasoline SI ICEV from the CURRENT TECHNOLOGY case. The range of FUTURE TECHNOLOGY, HIGH VOLUME costs used is half the difference between the low- and high-cost values found with Autonomie (Moawad et al. 2016). In this study, we assume that E85 vehicle costs are the same as for gasoline ICEVs and that LPG vehicles are 7% more expensive than gasoline ICEVs. All costs are multiplied by a factor of 1.5 to equate to an RPE with a 50% markup.

Table 38. Vehicle costs used in this study from the Autonomie model (Moawad et al. 2016)[a]

Vehicle Technology	CURRENT TECHNOLOGY, HIGH VOLUME (2013$)		FUTURE TECHNOLOGY, HIGH VOLUME (2013$)		
	Total Cost	Incremental Cost[a]	Total Cost	Incremental Cost[a]	Range
Gasoline/E85	21,384	–	23,491	2,107	±784
LPG	22,881	1,497	N/A	N/A	N/A
Diesel	24,697	3,313	25,839	4,455	±1,087
CNG	26,121	4,737	N/A	N/A	N/A
HEV	27,327	5,942	25,561	4,177	±1,097
PHEV10	30,029	8,645	26,150	4,766	±763
PHEV35	38,442	17,058	29,885	8,501	±1,475
H_2 FCEV	37,923	16,539	30,264	8,880	±1,991
BEV90	32,598	11,214	27,057	5,673	±2,289
BEV210	64,598	43,214	43,056	21,672	±7,246

[a] Incremental costs are relative to the CURRENT TECHNOLOGY, HIGH VOLUME gasoline ICEV.

Autonomie estimates for total vehicle manufacturing cost assume production at volume; however, it is important to recognize that the initial manufacture of advanced powertrain vehicles is likely to incur additional costs beyond those estimated at large scale. Accordingly, low-volume vehicle cost estimates of the current technology case provide context for the high-volume estimates shown in Table 38 by serving as an indication of the degree to which low-volume manufacturing could affect vehicle cost.

Low-volume vehicle cost estimates are calculated here by inflating the costs of those vehicle subsystems unique to advanced propulsion vehicles by a low-volume cost multiplier. For example, in a CNG SI ICEV, the storage tanks are produced at low volume, while the rest of the vehicle components can logically come from high-volume production lines serving both CNG SI ICEVs and other vehicles. For this low-volume CNG SI ICEV sensitivity, then, only the fuel tanks are subject to the low-volume cost multiplier. Other vehicle components subjected to the low-volume cost multiplier include batteries and motors for PHEVs, BEVs, and H_2 FCEVs, as well as the fuel cell and the hydrogen storage systems for H_2 FCEVs. The vehicle subsystem low-volume cost multiplier is based on low-volume production curves DOE developed for battery (Nelson et al. 2012), fuel cell (DOE 2015d), and hydrogen storage (DOE 2013b) technologies. A curve based on the average volume curves extracted from these three studies was used to estimate a low-volume cost multiplier of 2 (two times) for annual vehicle production of approximately 30,000 units (selected because of its position as the approximate logarithmic-scale midpoint of a scale-up from 10,000 units to 100,000 units).

In this sensitivity analysis, low-volume production is observed to have relatively large impacts on advanced technology vehicles, shown in Table 39 and Figure 13 for annual production of about 30,000 units. For the CNG ICEV, low-volume vehicle cost is approximately $5,000 higher (nearly 20% higher) than the high-volume CNG ICEV cost. PHEV low-volume cost is approximately $8,000–$20,000 higher (26–52% higher) than high-volume PHEV cost, depending on range; H_2 FCEV low-volume cost is approximately $17,500 higher (46% higher) than high-volume H_2 FCEV cost; and BEV low-volume cost is approximately $15,000–$47,000 higher (47–73% higher) than high-volume BEV cost, depending on range.

Table 39. Low-volume vehicle costs for vehicle technologies used in this study (based on Autonomie results from Moawad et al. 2016)[a]

Vehicle Technology	CURRENT TECHNOLOGY, HIGH VOLUME (2013$)		CURRENT TECHNOLOGY, LOW VOLUME (2013$)	
	Total Cost	Incremental Cost	Total Cost	Incremental Cost
Gasoline/E85	21,384	—	—	—
LPG	22,881	1,497	—	—
Diesel	24,697	3,313	—	—
CNG	26,121	4,737	31,289	9,905
HEV	27,327	5,942	—	—
PHEV10	30,029	8,645	37,944	16,560
PHEV35	38,442	17,058	58,604	37,220
H_2 FCEV	37,923	16,539	55,369	33,985
BEV90	32,598	11,214	47,849	26,465
BEV210	64,598	43,214	111,848	90,464

[a] Based on production of approximately 30,000 vehicles per year. Incremental costs are relative to the CURRENT TECHNOLOGY, HIGH VOLUME gasoline ICEV costs.

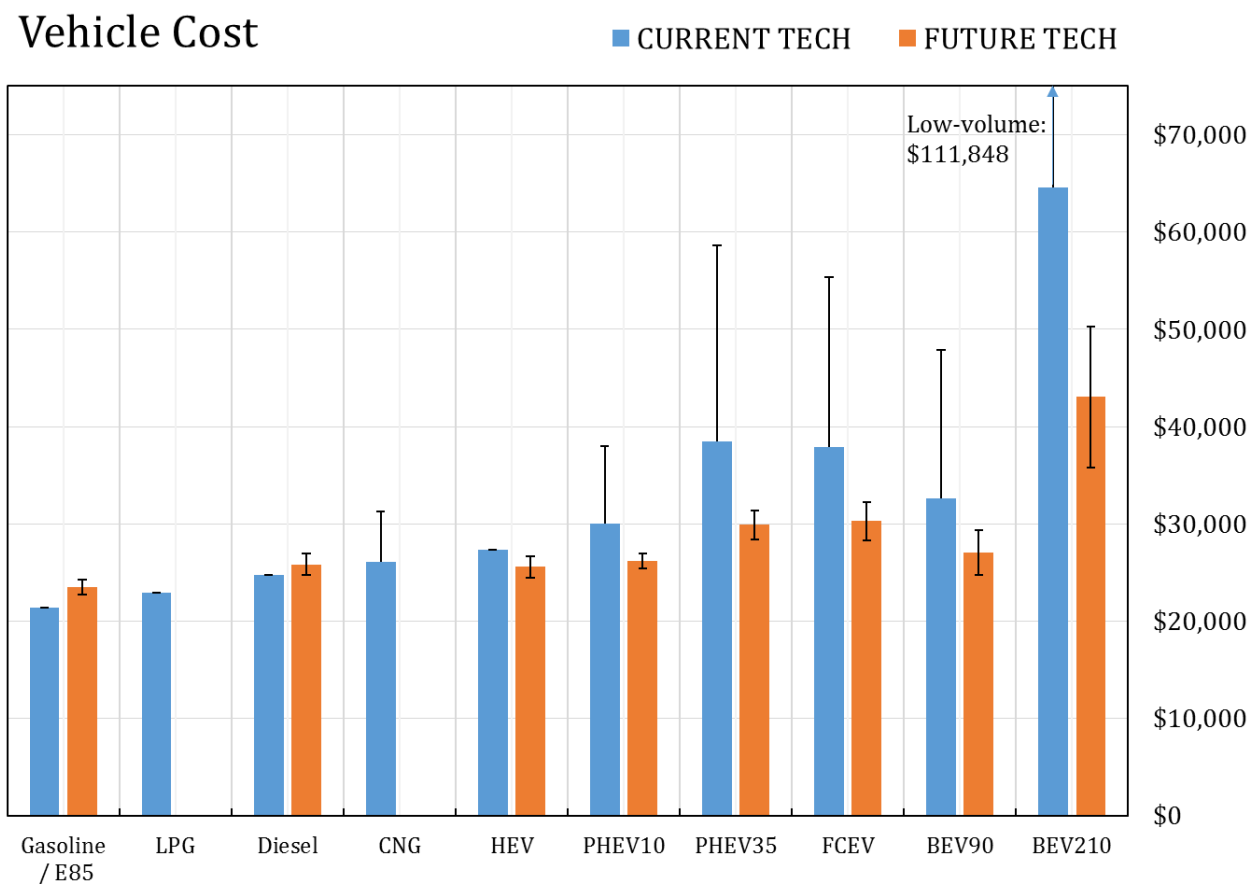

Figure 13. Summary of low-volume vehicle costs from Tables 38 and 39. Low-volume costs are shown as uncertainty bars for the CURRENT TECHNOLOGY case (with an arrow representing the off-scale high cost for low-volume BEV210 production). Uncertainty bars for FUTURE TECHNOLOGY cases are cost ranges from the Autonomie model.

6.6 References for Section 6

Argonne National Laboratory, Systems Assessment Group, 2014. *GREET Model, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. https://greet.es.anl.gov/index.php

Argonne, 2015. *GCTool: Design, Analyze and Compare Fuel Cell Systems and Power Plants*. http://www.anl.gov/technology/project/gctool-design-analyze-and-compare-fuel-cell-systems-and-power-plants

Cao, Q., S. Pagerit, R. Carlson, and A. Rousseau, 2007. "PHEV Hymotion Prius Model Validation and Control Improvements." In: *23rd International Electric Vehicle Symposium (EVS23)*, Anaheim, CA.

DOE (U.S. Department of Energy), Hydrogen and Fuel Cells Program, 2013b. *Record 13010: Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost*. https://www.hydrogen.energy.gov/program_records.html

DOE, Hydrogen and Fuel Cells Program, 2015d. *Record 15015: Fuel Cell System Cost – 2015*. https://www.hydrogen.energy.gov/program_records.html

Elgowainy, A., J. Han, L. Poch, M. Wang, A. Vyas, M. Mahalik, and A. Rousseau, 2010. *Well-to-wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles*. Report ANL-ESD-10-1, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-xkdaqgyk

EPA (U.S. Environmental Protection Agency), 2006. *Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates, Final Technical Support Document.* Report EPA420-R-06-017, Washington, DC. http://www3.epa.gov/carlabel/documents/420r06017.pdf

EPA, 2015b. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015*. Report EPA-420-R-15-016. http://www3.epa.gov/fueleconomy/fetrends/1975-2015/420r15016.pdf

Francfort, J., B. Bennett, R. Carlson, T. Garretson, L.L. Gourley, D. Karner, M. Kirkpatrick, P. McGuire, D. Scoffield, M. Shirk, S. Salisbury, S. Schey, J. Smart, S. White, and J. Wishart, 2015. *Plug-in Electric Vehicle and Infrastructure Analysis*. Report INL/EXT-15-35708, Idaho National Laboratory. http://avt.inel.gov/summaryreport.shtml

GPO (Government Printing Office), 2012. *2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule*. https://www.gpo.gov/fdsys/pkg/FR-2012-10-15/pdf/2012-21972.pdf

Kim, N., R. Carlson, F. Jehlik, and A. Rousseau, 2009. *Tahoe HEV Model Development in PSAT.* SAE Technical Paper 2009-01-1307, Warrendale, PA.

Moawad, A., N. Kim, N. Shidore, and A. Rousseau, 2016. *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies.* Report ANL/ESD-15/28, Argonne National Laboratory, Argonne, IL. http://www.autonomie.net/publications/fuel_economy_report.html

NHTSA (National Highway Traffic Safety Administration), National Center for Statistics and Analysis, 2006. *Vehicle Survivability and Travel Mileage Schedules*. http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf

Nelson, P.A., K.G. Gallagher, I. Bloom, and D.W. Dees, 2012. *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Second Edition.* Report ANL-12/55, Argonne National Laboratory. http://www.cse.anl.gov/batpac/files/BatPaC%20ANL-12_55.pdf

Pasquier, M., M. Duoba, and A. Rousseau, 2001. "Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedure." In: *The 18th International Electric Vehicle Symposium (EVS18)*, Berlin, Germany.

Rousseau, A., 2000. "Simulation and Validation of Hybrid Electric Vehicles Using AUTONOMIE." In: *The 3rd Global Powertrain Congress*, Detroit, MI.

Rousseau, A., J. Kwon, P. Sharer, S. Pagerit, and M. Duoba, 2006. "Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT." SAE Technical Paper 2006-01-0667, Warrendale, PA.

Stephens, T., Y. Zhou, A. Elgowainy, M. Duoba, A.D. Vyas, and A. Rousseau, 2013. *Estimating On-Road Fuel Economy of PHEVs from Test and Aggregated Data*. Presented at the Transportation Research Board 92nd Annual Meeting.

U.S. DRIVE Partnership, 2013. *Electrochemical Energy Storage Technical Team Roadmap*. http://energy.gov/eere/vehicles/downloads/us-drive-electrochemical-energy-storage-technical-team-roadmap

Weissler, P., 2009. "Many Factors Figure in Fuel-economy Calculation for Electric Vehicles." *Automot. Eng. Mag.*, 41.

7 VEHICLE PRODUCTION PATHWAYS

7.1 SYSTEM BOUNDARY FOR VEHICLE PRODUCTION PATHWAYS

The GREET2 model calculates vehicle-cycle energy use and emissions for various vehicle types and material compositions (Argonne 2014). The vehicle cycle includes the processes shown in Figure 14. This section elaborates the calculation of the material composition for the vehicle technologies used in this study and explains the major process assumptions on key material production and vehicle assembly, disposal, and recycling (ADR) processes. Using such input data, the vehicle manufacturing cycle results are estimated and presented.

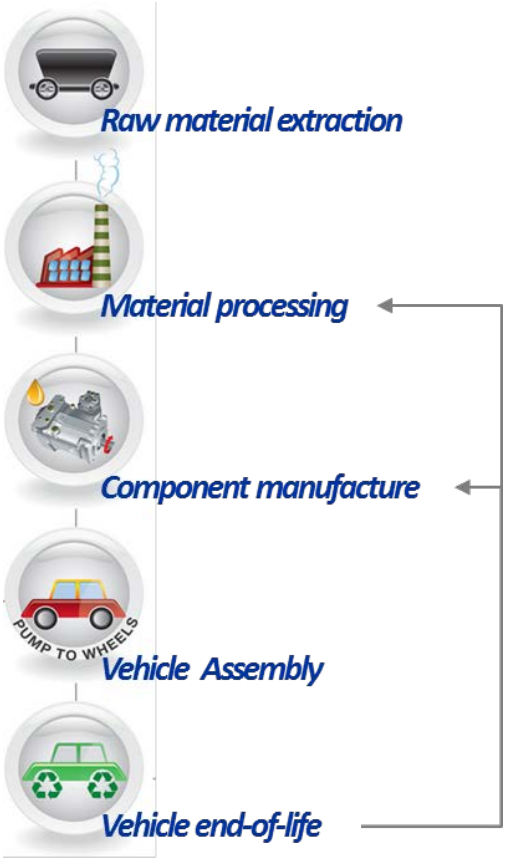

Figure 14. GREET vehicle manufacturing cycle

Figure 15 presents the process to estimate vehicle energy use and emissions using GREET. One of the key inputs for the vehicle manufacturing cycle analysis is vehicle component weight, which is presented in the previous section. For each major vehicle component, the vehicle manufacturing cycle model considers its material composition (i.e., steel, aluminum, iron, plastic, rubber, etc.). The model includes replacement schedules for components that are subject to replacement during a vehicle's lifetime (e.g., batteries, tires, and various vehicle fluids). For disposal and recycling, the model accounts for energy required and emissions generated during recycling of scrap materials for reuse. Finally, the model estimates the energy used during raw material recovery to vehicle assembly (e.g., mining through stamping) for vehicle manufacturing cycle simulations. Currently, for most of raw and processed materials in GREET2, energy use and emissions from transportation between processes are not taken into account. However, the impact of material transportation on C2G GHG emissions would be negligible.

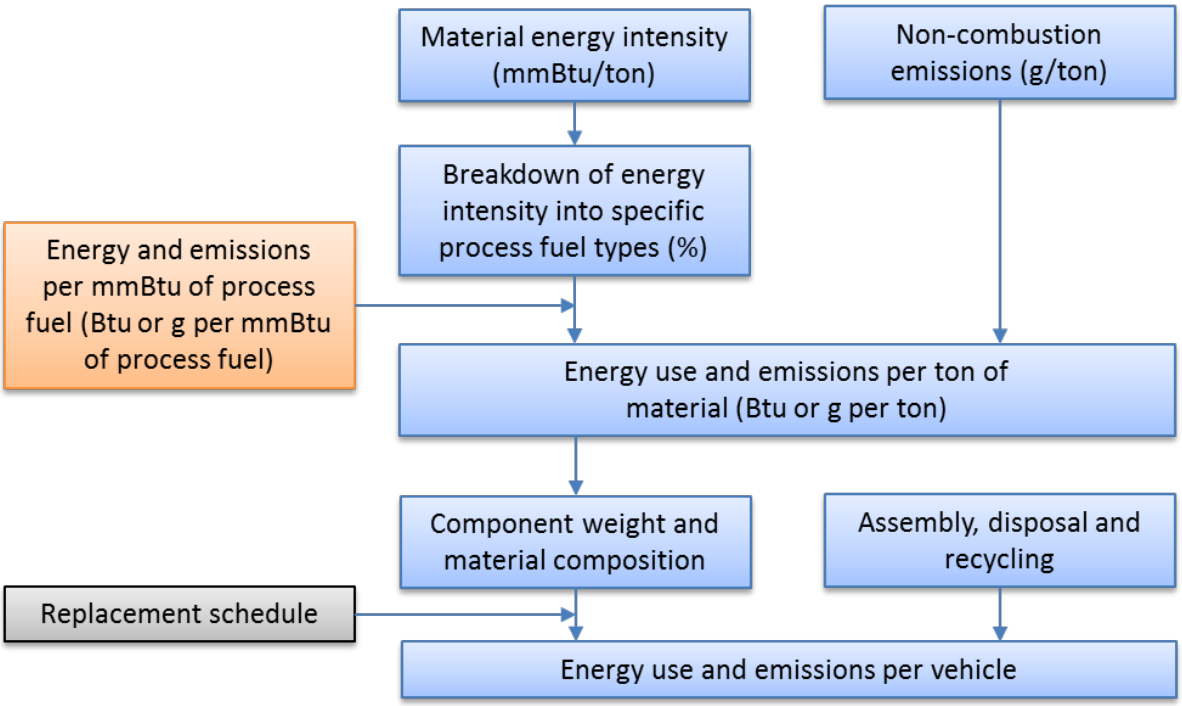

Figure 15. Process for GREET vehicle manufacturing cycle analysis

7.2 Material Composition for Each Component

The previous section provides the weight of vehicle components (e.g., glider, powertrain, transmission system, battery, traction motor and other electric machines/control, and wheels). Among them, the glider can be further divided into several subcomponents, such as body, exterior, chassis, and weld blanks and fasteners. Similarly, powertrain consists of engine, engine fuel storage system, power train thermal, fuel cell stack, fuel cell auxiliaries, exhaust, powertrain electrical, emission control electronics and weld blanks and fasteners. This study used the subcomponent weight distribution defined in GREET and provided in Table 40. The development of subcomponent weight distributions, documented in Burnham (2012), are based largely on the Automotive System Cost Model (ASCM) developed by IBIS Associates and Oak Ridge National Laboratory. ASCM compares the cost of vehicles at the system level and allows users to select various options at a system or component level to build a vehicle. Additional sources for subcomponent weight include vehicle simulation results using the Powertrain System Analysis Toolkit (Moawad et al. 2011), Carlson (2004), and other sources (Cooper 2004).

Since vehicle components and subcomponents contain more than one material, the material compositions of these components and subcomponents need to be estimated. Table 41 lists the material compositions for the vehicle components and subcomponents except for batteries, which are estimated in Burnham (2012). The material compositions are based on vehicle dismantling reports with additional information from (1) ASCM, (2) personal communications with Roy Muir at the U.S Council for Automotive Research / Vehicle Recycling Partnership (USCAR/VRP), Roy Cuenca at ANL, and Eric Carlson at TIAX (Carlson 2004; Cuenca 2005; Muir 2005), (3) literature review (Cooper 2004; James et al. 2014), and (4) Argonne assumptions. Note that, with the exception of transmission, the material compositions of each component or subcomponent are assumed to be consistent for all vehicle technologies. The

transmission systems of ICEVs have a different material composition from those of HEVs, FCEVs, and PHEVs.

Table 40. Subcomponent weight distribution (%)

Component	ICEV	HEV	PHEV	BEV	FCEV	Source
Glider (chassis, body, etc.)						
Body	41	41	41	41	41	ASCM
Exterior	4	4	4	4	4	ASCM
Interior	17	17	17	17	17	ASCM
Chassis	34	34	34	34	34	ASCM
Weld blanks and fasteners	4	4	4	4	4	ASCM
Powertrain						
Engine	57	48	46	–	–	ASCM; Moawad et al. (2011)
Fuel storage system	15	24	26	–	–	ASCM
Powertrain thermal	7	6	6	–	–	ASCM
Fuel cell stack	–	–	–	–	29	ASCM; Cooper (2004)
Fuel cell auxiliaries	–	–	–	–	71	ASCM; Carlson (2004); Cooper (2004)
Exhaust	13	13	12	–	–	ASCM
Powertrain electrical	3	4	5	–	–	ASCM
Emission controls	3	1	1	–	–	ASCM
Weld blanks and fasteners	3	4	5	–	–	ASCM

Even though the material compositions are consistent at a component or subcomponent level, the differences in vehicle component and subcomponent weight distributions result in different vehicle-level material compositions when the compositions are aggregated. For modeling purposes, the material composition of each component does not change between the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases. Table 42 presents material composition aggregated by component (excluding batteries). Steel accounts for the largest share of vehicle weight throughout all vehicle technologies (57–65%), followed by plastic (9–11%) and cast iron (2–13%). Wrought and cast aluminum, accounting for 1–6% and 4–9%, respectively, are key materials for vehicle manufacturing GHG emissions due to their high GHG intensity, even though their shares are smaller than steel, plastic, and cast iron. Stainless steel and carbon fiber reinforced plastic (CFRP) account for 4–5% and 4% of FCEV total weight, respectively. CFRP production is highly GHG intensive. Copper (2–7%), glass (2–3%), and rubber (2%) are also widely used in vehicles. Other minor materials include organic, magnesium, zinc, perfluorosulfonic acid, polytetrafluoroethylene, carbon paper, platinum, friction material, and nickel. ICEVs use lead-acid batteries, while HEVs, PHEVs, FCEVs, and BEVs are assumed to use Li-ion batteries with a small lead-acid battery. Table 43 presents the battery material composition, which is based on Cuenca et al. (1998) for lead-acid batteries and Dunn et al. (2015) for Li-ion batteries, using Argonne National Laboratory's Battery Performance and Cost (BatPaC) model (Nelson et al. 2011).

The Battery Performance and Cost (BatPaC) model (Nelson et al. 2011) adopts a prismatic pouch cell structure, which is made of a tri-layer polymer/aluminum material. Aluminum and copper foils serve as the current collectors at the cathode and anode, respectively. The anode is coated on both sides with graphite. The cathode material can be one of five chemistries, as described below. A polymeric binder

Table 41. Material composition of components and subcomponents, except for battery (%)

Component	Steel	Cast Iron	Wrought Aluminum	Cast Aluminum	Copper	Glass	Average Plastic [a]	Rubber	Stainless Steel	CFRP	Others	Source
Glider (chassis, body, etc.)												
Body	87	–	–	–	–	10	2	–	–	–	–	ASCM; dismantling reports
Exterior	1	–	–	–	12	–	45	6	–	–	35	ASCM; dismantling reports
Interior	40	–	3	–	5	–	45	–	–	–	8	Dismantling reports
Chassis	79	7	1	–	1	–	2	9	–	–	1	ASCM; Cuenca (2005); Muir (2005); Argonne assumptions
Weld blanks and fasteners	63	–	–	–	–	–	38	–	–	–	–	Dismantling reports; Argonne assumptions
Powertrain												
Engine	10	50	–	30	1	–	5	5	–	–	–	Muir (2005); Argonne assumptions
Engine fuel storage system	100	–	–	–	–	–	–	–	–	–	–	Cuenca (2005)
Powertrain thermal	50	–	–	–	–	–	50	–	–	–	–	Dismantling reports; Argonne assumptions
Fuel cell stack	–	–	–	–	–	–	24	–	65	–	11	James et al. (2014)
Fuel cell auxiliaries	37	–	17	–	10	–	9	2	–	26	1	Cooper (2004); Carlson (2004)
Exhaust	100	–	–	–	–	–	–	–	–	–	–	Cuenca (2005) Argonne assumptions
Powertrain electrical	–	–	–	–	41	–	59	–	–	–	–	Dismantling reports
Emission controls	–	–	–	–	41	–	59	–	–	–	–	Dismantling reports
Weld blanks and fasteners	100	–	–	–	–	–	–	–	–	–	–	Dismantling reports; Argonne assumptions
Transmission												
ICEV	30	30	30	–	–	–	5	5	–	–	–	Muir (2005); Argonne assumptions
HEV, FCEV, and PHEV	61	–	20	–	19	–	–	–	–	–	–	Dismantling reports
Traction motor	36	–	–	36	28	–	–	–	–	–	–	Dismantling reports
Wheels component (50% wheels and 50% tires by mass)												
Wheels	100	–	–	–	–	–	–	–	–	–	–	ASCM
Tires	33	–	–	–	–	–	–	67	–	–	–	Muir (2005); Argonne assumptions

[a] See Table 47 for the share of average plastic in a vehicle.

Table 42. Material composition aggregated by component except for battery (%)

CURRENT TECHNOLOGY	Gasoline ICEV	E85 ICEV	CNG ICEV	Diesel ICEV	Gasoline HEV	H_2 FCEV	BEV90	BEV210	PHEV10	PHEV35
Steel	63	63	61	62	64	58	65	65	64	62
Cast iron	10	10	12	11	6	2	2	2	5	5
Wrought aluminum	2	2	2	2	1	4	1	1	1	1
Cast aluminum	4	4	5	5	7	4	7	8	7	9
Copper	2	2	2	2	6	6	6	7	6	7
Glass	3	3	3	3	3	3	3	3	3	2
Average plastic	11	11	11	11	10	11	10	10	10	9
Rubber	2	2	2	2	2	2	2	2	2	2
Stainless steel	–	–	–	–	–	4	–	–	–	–
CFRP	–	–	–	–	–	4	–	–	–	–
Others	2	2	2	2	2	3	3	3	2	2
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV**	**BEV90**	**BEV210**	**PHEV10**	**PHEV35**
Steel	61	62	60	60	64	57	64	64	64	63
Cast iron	12	11	13	13	6	2	2	2	6	5
Wrought aluminum	2	2	2	2	1	4	2	2	1	1
Cast aluminum	5	5	6	6	7	4	8	8	7	9
Copper	2	2	2	2	5	6	7	7	5	7
Glass	3	3	2	2	3	3	3	3	3	2
Average plastic	11	11	11	11	10	12	10	10	10	9
Rubber	2	2	2	2	2	2	2	2	2	2
Stainless steel	–	–	–	–	–	5	–	–	–	–
CFRP	–	–	–	–	–	4	–	–	–	–
Others	2	2	2	2	2	3	3	3	2	2

Table 43. Material composition of battery (%)

Material	Lead-Acid Battery	Li-ion Battery			
		Gasoline HEV and H_2 FCEV	BEV90 and BEV210	PHEV10	PHEV35
Lead	69	–	–	–	–
Active material ($LiMn_2O_4$)	–	25	34	30	27
Wrought aluminum	–	20	19	21	22
Copper	–	12	11	11	15
Graphite/carbon	–	11	15	13	12
Electronic parts	–	11	1	4	3
Plastic: polypropylene	6	2	2	2	2
Plastic: polyethylene terephthalate	–	2	1	2	2
Electrolyte: ethylene carbonate	–	4	5	5	5
Electrolyte: dimethyl carbonate	–	4	5	5	5
Electrolyte: $LiPF_6$	–	1	2	2	2
Steel	–	3	1	2	2
Coolant: glycol	–	2	1	2	1
Binder	–	2	3	2	2
Water	14	–	–	–	–
Sulfuric acid	8	–	–	–	–
Fiberglass	2	–	–	–	–
Others	1	–	–	–	–

material holds the active material particles together, and a porous membrane separates the two electrodes. BatPaC models the electrolyte as $LiPF_6$ (lithium hexafluorophosphate) in an organic solvent containing linear and cyclic carbonates. During discharge, the lithium ions move from the anode to the cathode while the electrons travel through the current collectors and the external circuit to perform external work. BatPaC models these cells as being enclosed in a module; there are six modules per battery.

To estimate the manufacturing cost of a battery pack, BatPaC users can change design requirements and select from among the following five battery chemistries:

- Lithium nickel cobalt aluminum oxide with a graphite electrode (NCA-G)
- Lithium nickel manganese cobalt oxide with a graphite electrode (NMC-G)
- Lithium iron phosphate with a graphite electrode (LFP-G)
- Lithium manganese spinel with a titanium dioxide electrode (LMO-LTO)
- Lithium manganese oxide spinel with a graphite electrode (LMO-G).

This study uses LMO-G, the default battery chemistry in GREET, because LMO is relatively cheap with high power density (Dunn et al. 2014c). It is also widely used in current PHEVs. The drawbacks of LMO include lower energy density and accelerated capacity fade. Thus, for high-capacity applications (e.g., BEVs and PHEV35), other battery chemistries could be considered, such as NMC or NCA, which is used in current longer-range BEVs.

7.3 Key Material for Vehicle Production Pathways

Once the materials used in the vehicles are estimated, the production processes and, if possible, the recycling processes for each material need to be characterized to estimate the amount of energy used during the vehicle production. For each material, this study characterized raw material sources, production and fabrication processes, and recycling processes for major materials for vehicle production pathways, including steel, cast iron, aluminum, plastics, lead, glass, rubber, copper, and battery materials. This section explains the key production assumptions for each process associated with the key materials.

7.3.1 Steel Production Pathways

Figure 16 presents the steel production flowchart modeled in GREET. The first step in steelmaking is extracting iron ore (usually taconite in the United States), which involves mining the ore by blasting and further processing it to concentrate the ore to a purity of at least 66% before it can be used in steelmaking. First the ore is crushed into a fine powder, then the metal is magnetically separated from the waste rock. The powder is wet down and then rolled with clay inside a large rotating cylinder; it is then heated and cooled to form iron ore pellets.

Coking involves heating metallurgical coal in the absence of oxygen to drive off 25% to 30% of its mass as volatiles, producing a carbonaceous product called coke, which is used both as a fuel and reducing agent in blast furnaces. The process also produces coke oven gas (COG), which is a high-quality fuel that is also used in the blast furnace. Two major by-products, coal tar and chemicals extracted from the gas, also result from this process. The coking process is a major source of both gaseous emissions and particulates. Gaseous emissions include CH_4, CO, H_2, and other hydrocarbons, which are the major constituents of COG. Sulfur oxide emissions depend on the sulfur content of the coal feed and the underfired gas, which can potentially be NG, COG, or blast furnace gas. Benzene and other toxic volatile organic carbon (VOC) emissions from the by-product chemical plant have been a particular concern. Coal dust may be released during oven charging.

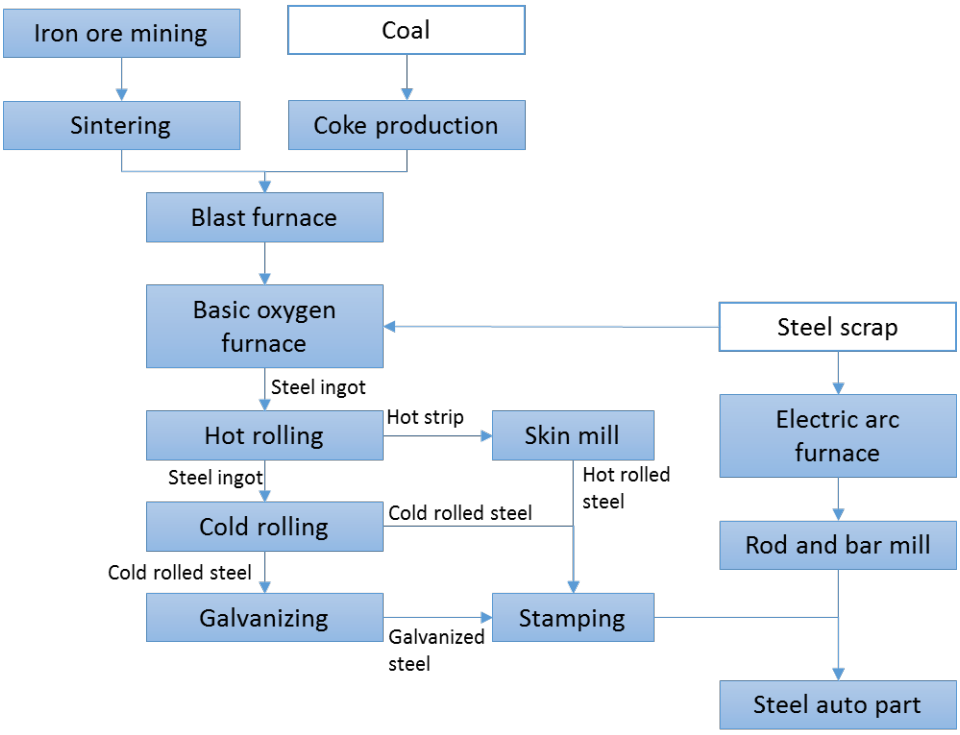

Figure 16. Steel production steps

An intermediate product in steelmaking, called sinter, is produced from a mixture of fine iron ore powder, coke, limestone ($CaCO_3$), dolomite, and flue dust that is ignited by a gas-fired furnace and fused into a porous cake-like substance. This process can release a significant amount of CO. Both the iron ore pellets and the sinter are fed to blast furnaces to produce molten iron, which is a crude, high-carbon form of iron. The blast furnace also produces a fuel gas that can be used for coke production or electricity generation. Then, a basic oxygen furnace is used to convert the molten iron to steel. First, the molten iron is poured into a large ladle, where magnesium is added to reduce sulfur impurities. Next, it is poured into a vessel where 99% pure oxygen is blown onto the iron. Next, the iron is poured into a furnace where various alloying materials are added, depending on the end use. The resulting steel is poured into an ingot mold and allowed to cool.

The ingots are then hot rolled to produce steel strips. Depending on the application, the hot strips could go through skin milling to produce hot rolled sheets or through cold rolling to produce cold rolled-sheets with further reduced thickness and desirable material characteristics. Cold-rolled sheets can be further galvanized to prevent corrosion. Finally, the steel sheet is stamped to shape the sheet into automotive parts, such as body panels and body-in-white structures.

Recycled steel and stainless steel are produced from steel scrap via the electric arc process, in which an electric arc is passed through graphite electrodes that are lowered into the furnace to melt the scrap. Limestone is added to form a slag that removes impurities. The resulting steel is poured into an ingot mold and allowed to cool.

Table 44 lists the process assumptions for steel production, including fuel consumption, input material, and non-combustion emissions. Note that intermediate products can be input for subsequent processes. For example, 1 ton of cold-rolled steel requires 1.05 ton of hot steel strip, which itself requires 1.08 ton of steel ingot from the basic oxygen furnace. Note that 1.04 and 1.61 short tons of intermediate steel from an electric arc furnace are needed per short ton of recycled and stainless steel products, respectively.

7.3.2 Cast Iron Production Pathway

Cast iron parts for automobiles, such as engine blocks, can be produced by automakers in their own foundries, using scrap iron and steel as the raw materials. Scrap is reduced in size by shredding, shearing, cutting, or crushing, depending on the source, and charged to a cupola furnace, which resembles a small blast furnace. Foundry coke, similar to metallurgical coke but slightly more energy-intensive, supplies the heat to melt the metal, which is then poured into molds. Table 45 summarizes the process assumptions for cast iron production.

7.3.3 Aluminum Production Pathway

Figure 17 illustrates wrought and cast aluminum production. The virgin aluminum production pathway starts with extracting bauxite ore, which involves mining the ore by using blasting, basic processing steps to facilitate handling and refining, and transportation of the ore to the refining plant. Then, alumina production using the Bayer process involves washing the bauxite with lime and a heated (250°C) solution of lye in a digester. GREET assumes sodium hydroxide (NaOH) is used as lye. When the solution of lye is cooled, aluminum hydroxide [$Al(OH)_3$] crystals precipitate out, which are heated again to produce alumina (Al_2O_3).

The Hall-Héroult process dissolves the alumina in a carbon-lined steel tank filled with molten cryolite (Na_3AlF_6) and aluminum fluoride (AlF_3), which form an electrolyte solution. A direct current is passed through the solution, breaking the aluminum and oxygen bonds to form a dense liquid aluminum that sinks to the bottom. Emissions from this aluminum reduction process include gaseous tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6), whose global warming potential is significantly higher than that of

Table 44. Process assumptions for steel production (per short ton of product)

Input/Emission and Unit		Virgin steel										Recycled/stainless steel		
			Steel production											
		Iron Ore Extraction and Processing [a]	Coke Production [a]	Sintering [a]	Blast Furnace[a]	Basic Oxygen Furnace [a]	Hot rolling[a]	Skin Mill[a]	Cold Rolling[a]	Galvanizing[a]	Stamping[b]	Electric Arc Furnace[a]	Rod and Bar Mill[a]	Machining[c]
Input fuel														
Residual oil	MMBtu	0.18	–	–	1.13	–	–	–	–	–	–	–	–	–
Gasoline	MMBtu	–	–	–	–	–	–	–	–	–	–	–	–	–
Diesel	MMBtu	0.03	–	–	–	–	–	–	–	–	–	–	–	–
NG	MMBtu	0.19	–	–	0.30	0.04	0.63	–	–	–	4.31	1.19	2.16	–
Coal	MMBtu	–	15.41	–	–	–	–	–	–	–	–	–	–	–
Electricity	MMBtu	1.39	0.17	0.06	0.35	0.65	0.70	0.04	1.40	0.70	1.15	4.99	1.08	0.54
Intermediate fuel														
Coke	MMBtu	–	–	0.15	10.07	–	–	–	–	–	–	0.17	–	–
Blast furnace	MMBtu	–	0.36	–	–	0.33	0.03	0.03	0.25	0.18	–	–	–	–
Coke oven	MMBtu	–	–	0.02	0.55	0.06	1.29	–	0.34	1.12	–	–	–	–
Material														
Limestone	ton	–	–	0.009	0.043	–	–	–	–	–	–	–	–	–
Lime	ton	–	–	–	–	0.063	–	–	–	–	–	–	–	–
Iron ore	ton	–	–	0.002	1.144	–	–	–	–	–	–	–	–	–
Intermediate	ton	–	–	–	–	–	1.03	1.02	1.05	1.00	1.34	–	1.04/1.61 [d]	1.00
Non-combustion emissions														
VOC	ton	–	0.002	–	0.001	–	–	–	–	–	–	–	–	–
CO	ton	–	–	0.003	0.016	0.002	–	–	–	–	–	0.003	–	–
CO_2	ton	–	–	0.032	0.026	–	–	–	–	–	–	0.026	–	–

[a] Source: Markus Engineering Services (2002).

[b] Source: Burnham et al. (2006).

[c] Source: Sullivan et al. (2010).

[d] 1.04 and 1.61 short tons of intermediate steel from electric arc furnace are needed per short ton of recycled and stainless steel products, respectively.

Table 45. Process assumptions for cast iron production.

Fuel	Unit	Iron Recycling[a]	Iron Casting[a]	Iron Forging[b]	Machining[b]
Diesel	MMBtu/ton	1.25	–	–	–
NG	MMBtu/ton	–	–	32.6	–
Electricity	MMBtu/ton	0.09	–	1.18	0.54
Coke	ton/ton	–	0.84	–	–

[a] Sources: Burnham et al. (2006); Cuenca (2005).

[b] Source: Sullivan et al. (2010).

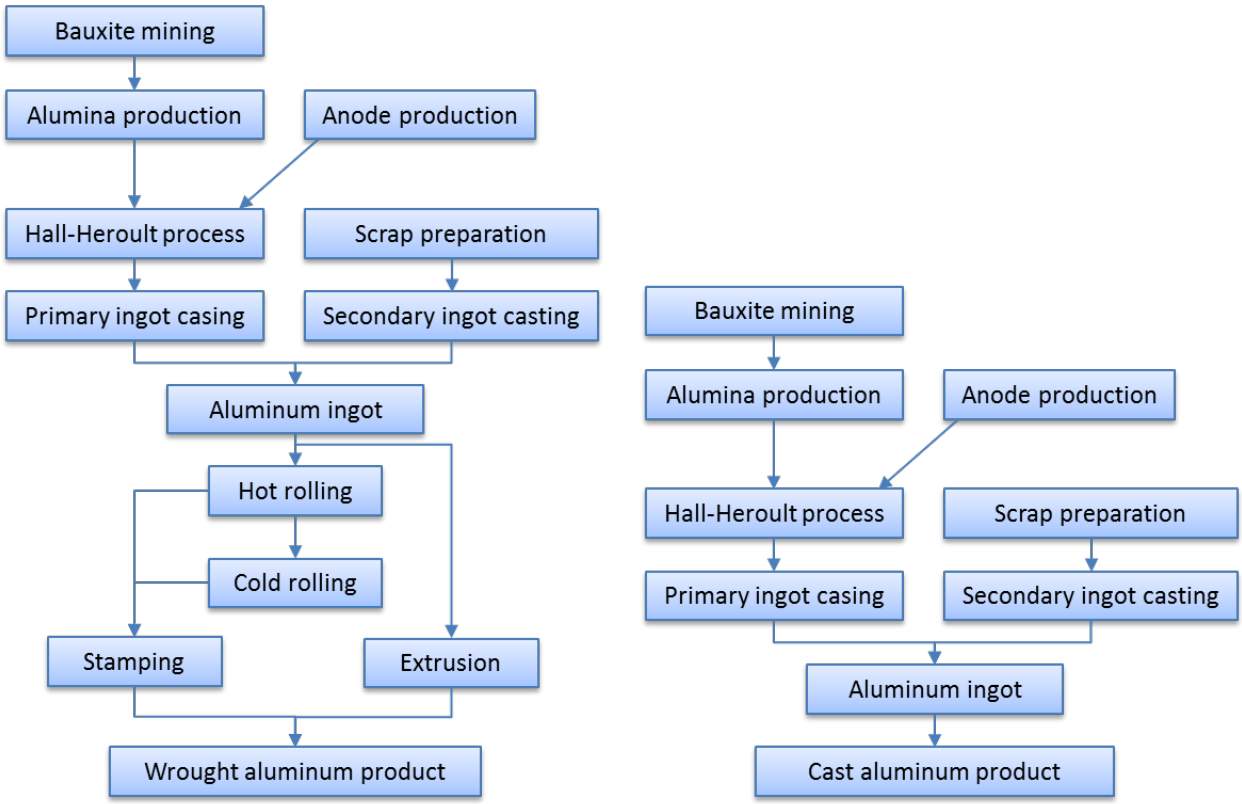

Figure 17. Wrought and cast aluminum production steps

CO_2, CH_4, and N_2O: the 100-year global warming potential is 6,630 for CF_4 and 11,100 for C_2F_6. The liquid aluminum is cooled to form ingots for subsequent automotive parts production.

Recycled aluminum production involves scrap preparation, melting, and ingot casting. Aluminum scrap is melted in large, NG-fired reverberatory furnaces and poured into ingot molds. Alloy compatibility is a major concern for producing quality automotive parts from recycled materials. Thus, for large-scale recycling of aluminum automotive parts, the cast and wrought materials are typically separated so that the chemistry of the recycled parts is predictable and desirable. Thus, GREET uses different assumptions for wrought and cast aluminum scrap preparation.

Table 46 lists the input fuel and material and non-combustion emissions associated with aluminum production pathways, which are similar to those of steel production. Keoleian et al. (2012) processed the 2010 lifecycle assessment report by PE Americas prepared for the Aluminum Association, a U.S.-based

Table 46. Process assumptions for aluminum production (per ton finished aluminum product)

Input	Unit	Virgin Aluminum					Recycled Aluminum			Wrought Aluminum Production			Cast Aluminum Production		
		Bauxite Mining[a]	Alumina Production[a]	Anode Production[a]	Hall-Héroult Process[a]	Primary Ingot Casting[a]	Wrought Al Scrap Preparation[b]	Cast Al Scrap Preparation[b]	Secondary Ingot Casting[a]	Hot Rolling[a]	Cold Rolling[a]	Stamping[a]	Extrusion[b]	Shape Casting[a]	Machining[c]
Fuel															
Residual oil	MMBtu	0.05	6.76	0.08	–	–	–	–	0.59	–	–	–	–	–	–
Diesel	MMBtu	0.22	0.05	0.02	–	0.12	0.39	1.35	0.01	–	–	–	0.02	–	–
Gasoline	MMBtu	–	–	–	–	–	–	–	–	–	0.06	–	–	–	–
NG	MMBtu	–	6.79	0.89	–	1.04	–	–	1.63	1.05	0.78	4.31	3.21	7.57	–
Coal	MMBtu	–	2.63	0.04	–	0.07	–	–	–	–	–	–	0.22	–	–
LPG	MMBtu	–	–	–	–	–	–	–	0.01	–	–	–	0.09	–	–
Electricity	MMBtu	0.03	0.75	0.18	48.13	0.22	0.24	0.10	0.65	0.82	1.08	1.15	0.29	–	0.54
Material															
NaOH	ton	–	0.172	–	–	–	–	–	–	–	–	–	–	–	–
Lime	ton	–	0.076	–	–	–	–	–	–	–	–	–	–	–	–
Coke	ton	–	–	0.438	–	–	–	–	–	–	–	–	–	–	–
Steel sheet	ton	–	–	0.002	0.008	–	–	–	–	–	–	–	–	–	–
Intermediate aluminum	ton	–	–	–	–	–	1.060	1.000	1.043	1.011	1.007	1.380	1.003	1.107	1.000
Non-combustion emissions															
CF_4	g	–	–	–	62.42	–	–	–	–	–	–	–	–	–	–
C_2F_6	g	–	–	–	7.45	–	–	–	–	–	–	–	–	–	–
CO_2	ton	–	–	0.122	0.122	–	–	–	–	–	–	–	–	–	–

[a] Source: Keoleian et al. (2012).
[b] Source: Burnham et al. (2006).
[c] Source: Sullivan et al. (2010).

aluminum industry group (PE Americas, 2010). The PE Americas report is based on primary production data from the International Aluminum Institute surveys, representing 2006 North American industry data. The 2010 report by PE Americas, however, was specific to the aluminum can industry, which has particular recycling procedures that are not necessarily representative of aluminum recycling in general. Thus, GREET uses the assumptions in Burnham et al. (2006) based on Aluminum Association (1998). This report provides information from 1995 as part of the United States Automotive Materials Partnership initiative. Note that, in its latest version, GREET has updated aluminum production assumptions based on 2011 North American industry data (Aluminum Association 2013). However, the updated version of GREET was not used in this study.

7.3.4 Plastic and CFRP Production Pathways

Plastics are made from petroleum derivatives or NG liquids via a series of chemical reactions that produce a building block or monomer, which is then reacted with itself or other monomers—often at elevated temperatures or pressures—to form a polymer or plastic. Different vehicle applications require different types of plastics. For example, Sullivan et al. (1998) provides the percent by weight of 16 types of plastic in an average family sedan, shown in Table 47. The types of plastic includes acrylonitrile butadiene styrene (ABS), ethylene propylene diene monomer (EPDM), liquid epoxy, general purpose polystyrene (GPPS), high-impact polystyrene (HIPS), high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), nylon 6, nylon 66, polycarbonate (PC), polyethylene terephthalate (PET), polypropylene (PP), polyurethane (PUR) flexible foam, PUR rigid foam, and polyvinyl chloride (PVC). Table 47 also provide the resin production energy for the 16 plastic types based on Keoleian et al. (2012), which analyzed the data from Franklin Associates (2011, 2001), Plastics Europe (2010), Sullivan et al. (2010), and Brown et al. (1996).

Table 47. Energy use for plastic resin production and share of individual plastic in a vehicle

Plastic Type	Resin Production Energy (MMBtu/ton)	Shares of Individual Plastic in a Vehicle (%)	
		Average Plastic	CFRP
ABS[a]	23.9	8	–
EPDM[a]	7.4	7	–
Liquid epoxy[a]	58.7	11	30
GPPS[a]	22.7	1	–
HIPS[a]	22.4	1	–
HDPE[a]	11.2	1	–
LDPE[a]	14.6	1	–
LLDPE[a]	10.8	1	–
Nylon 6[a]	52.2	1	–
Nylon 66[a]	51.2	7	–
PC[a]	42.6	4	–
PET[a]	18.2	2	–
PP[a]	9.3	18	–
PUR flexible foam[a]	27.2	12	–
PUR rigid foam[a]	24.4	12	–
PVC[a]	18.3	14	–
Carbon fiber[b]	399	–	70

[a] Source: Keoleian et al. (2012).
[b] Source: Burnham et al. (2006).

Table 48 provides the key assumptions (e.g., amount of resin inputs per ton of product and transformation energy inputs) of plastic transformation processes, which transform plastic resins into semi-finished products by extrusion, injection molding, blow molding, compression molding, and calendaring. Transformation process data for ABS, EPDM, nylon 6, and nylon 66 are not available. Therefore, polyethylene (PE) extrusion and PP injection molding processes are used as surrogate transformation processes.

Table 48 also provides weight distribution of transformation processes for each resin used in a vehicle based on Sullivan et al. (1998). For example, average HDPE products in a vehicle consist of HDPE from injection molding (67%), compression molding (24%), and extrusion (9%).

Table 48. Plastic transformation process assumptions

Input or Plastic Type	CFRP Transformation[a]	PE Transformation		PP Transformation		PVC Transformation			Universal	
		Extrusion[b]	Injection Molding[b]	Extrusion[b]	Injection Molding[b]	Calendaring[b]	Extrusion[b]	Injection Molding[b]	Blow Molding[b]	Compression Molding[b]
Resin (ton/ton)	1.14	0.95	1.01	1.00	1.14	1.16	1.00	1.03	1.00	1.00
Energy (MMBtu/ton)	7.89	1.70	6.19	2.17	2.47	1.80	1.63	3.80	5.31	6.27
Transformation process share for individual plastic (%)										
CFRP	100	–	–	–	–	–	–	–	–	–
HDPE	–	9	67	–	–	–	–	–	–	24
LDPE	–	9	67	–	–	–	–	–	–	24
LLDPE	–	9	67	–	–	–	–	–	–	24
PC	–	–	–	–	78	–	–	–	–	22
PET	–	–	–	–	50	–	–	–	–	50
PP	–	–	–	2	74	–	–	–	9	15
PVC	–	–	–	–	–	18	51	29	–	2
ABS	–	18	–	–	59	–	–	–	–	24
EPDM	–	28	–	–	41	–	–	–	–	32
Nylon 6	–	–	–	–	18	–	–	–	36	45
Nylon 66	–	30	–	–	36	–	–	–	–	34

[a] Source: Burnham et al. (2006).

[b] Source: Keoleian et al. (2012).

CFRP has been used in aerospace, bicycles, and other applications because of its high strength and light weight; however, the high cost of carbon fiber has limited its use in automotive applications. GREET assumes that CFRP is used for H_2 storage tanks. As shown in Table 48, CFRP for H_2 storage tanks contains 70% carbon fiber and 30% liquid epoxy.

Carbon fiber is made out of long, thin sheets of a type of carbon similar to graphite. The most common means of production is the oxidation and thermal pyrolysis of polyacrylonitrile (PAN). When PAN, a polymer, is heated, the molecular chains bond together and form planar sheets of carbon atoms called

grapheme, which merge to form a tubular filament or "fiber." The fibers are then enhanced to make high-strength carbon through heat treatment. The high cost of carbon fiber is attributable primarily to the complexity of the production process. In addition to its high cost, carbon fiber production is very energy-intensive (Cuenca et al. 1998).

7.3.5 Li-ion Battery Production Pathways

Figure 18 presents the components and processes with material and energy flows in GREET for Li-ion battery production using LMO, which consists of five major material pathways: cathode active materials (LMO), anode active material (graphite), binder (polyvinylidene fluoride, PVDF), electrolyte, and the battery management system (BMS).

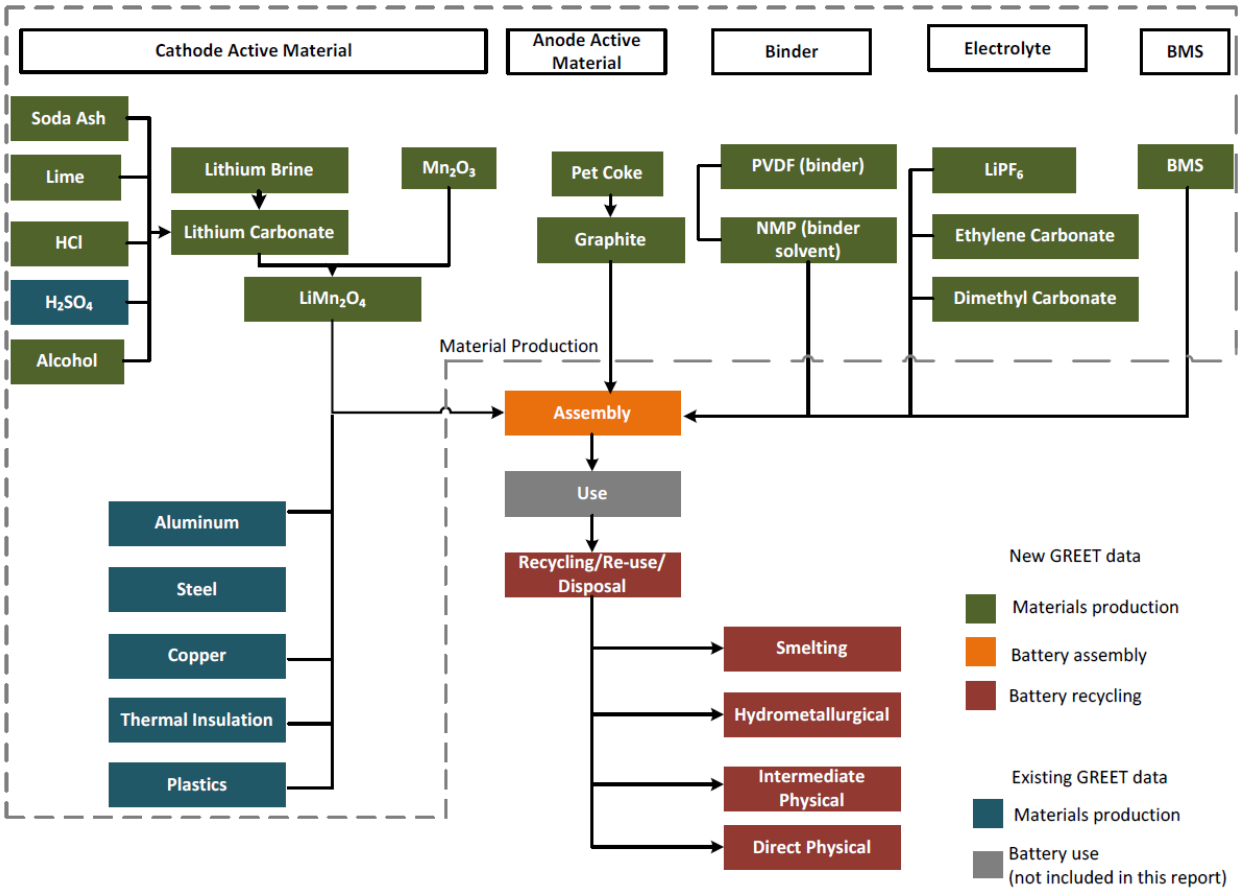

Figure 18. Li-ion battery production material and energy flows in GREET (Dunn et al. 2014b)

A raw material for LMO production is lithium carbonate (Li_2CO_3), which can be produced from concentrated lithium brine. Sources of lithium include brine, pegmatites, or sedimentary rocks (Gruber et al. 2011). Brine is currently the most common source, much of it originating from the Salar de Atacama in Chile (Gruber et al. 2011). Note that five companies produce the lion's share of lithium from brines (Glauser and Inoguchi 2011). Dunn et al. (2014b) developed GREET's LMO module based on the data for one operation in Chile and one in Nevada. Between the two sources, this study uses the LMO from Chilean lithium brine since this pathway represents the largest share of Li-ion battery used in the United States. Dunn et al. (2014b) also modeled three recycled LMO pathways, which are not considered in this study. Brine, with a lithium concentration of 1,500 ppm, is pumped from wells; the liquid evaporates under controlled conditions in a series of ponds until the lithium concentration is 60,000 ppm.

From the concentrated Li brine, boron is removed through addition of hydrogen chloride (HCl), alcohol, an organic solvent, and sulfuric acid (H_2SO_4). In the subsequent first extraction phase, magnesium carbonate ($MgCO_3$) precipitates out of the solution following the addition of soda ash. In the second extraction stage, lime is used to force magnesium hydroxide [$Mg(OH)_2$] and calcium carbonate ($CaCO_3$) out of solution. The purified lithium brine moves to the precipitation reactor, where soda ash is added to the solution and Li_2CO3 precipitates. The resulting solid is washed, filtered, dried, and packaged (SQM 2001). In addition to Li_2CO_3, manganese oxide (Mn_2O_3) is needed for LMO production. Manganese can also be in the form of a salt or Mn_3O_4. Mn_2O_3 is made by heating manganese ore in a kiln operating at temperatures between 500°C and 800°C. Dunn et al. (2014b) developed an estimate for the energy consumed during this step by using data from industrial processes (Brown et al. 1996), and also calculated process CO_2 emissions during Mn_2O_3 production from the stoichiometry (2 mol CO_2 per mol Mn_2O_3). Finally, from Li_2CO_3 and Mn_2O_3, LMO is produced in a kiln. For LMO production, Dunn et al. (2014b) adopted values from the literature (Notter et al. 2010) and assuming that process heat is derived from NG. We used stoichiometry (1 mol CO_2 per 2 mol $LiMn_2O_4$) to calculate process CO_2 emissions.

For the anode, the production of graphite from calcined coke includes two high-temperature steps. The aluminum industry uses graphite electrodes for the electrolysis of alumina in the Hall-Héroult process. Thus, Dunn et al. (2014b) assumed that the graphite electrodes used in aluminum production are comparable to the graphite anodes used in Li-ion batteries. To bind the electrode materials together, PVDF is widely used in Li-ion batteries. Since energy and emissions data for PVDF were not available, Dunn et al. (2014b) adopted the energy intensity of PVC production for that of PVDF. $LiPF_6$ is the electrolyte for many Li-ion batteries and often mixed with ethylene carbonate and dimethyl carbonate to increase permittivity. Dimethyl carbonate can be made from ethylene carbonate, which in turn, is made from ethylene oxide. Dunn et al. (2014b) compiled material and energy flow data for these materials from data for individual production steps (Espinosa et al. 2011; Plastics Europe 2010).

The BMS is the collection of electronic components (e.g., semiconductors, circuit boards, sensors) that measure and monitor cell voltage, temperature, and current and perform basic battery functions such as cell balancing and ensuring battery longevity and safety. Semiconductor manufacturing involves highly controlled metal deposition and chemical etching processes. Dunn et al. (2014b) developed material and energy flows for BMS production based on areas for two separate pieces of the BMS that involve different energy intensities for manufacture: circuit boards and semiconductors. Then, they adopted energy intensity factors for the production of circuit boards and semiconductors from Deng et al. (2011) to calculate the energy to produce a given BMS mass.

N-methyl-2-pyrrolidone (NMP) is used as a solvent during the battery manufacturing, although none remains in the final battery. About 99.5% of the NMP is recovered and can be reused, but the balance is combusted and must be replaced (Nelson et al. 2011). Energy consumption data for the production of NMP is derived from Sutter (2007). Dunn et al. (2014b) did not include the burdens associated with producing the raw materials for NMP (butyrolactone and methyl amine) because the Li-ion battery consumes little NMP.

Table 49 provides the key assumptions for the Li-ion battery production pathway developed in Dunn et al. (2014b) from extensive literature review on Li-ion battery materials, as described above. Since Li_2CO_3 is produced in Chile, the 2009 Chilean electricity mix is used for the processes: 41.7% hydropower, 24.5% coal, 20.0% oil, 7.0% biofuels, 6.5% NG, 0.13% wind, and 0.16% other (IEA 2012).

Dunn et al. (2012b) estimated the energy intensity of the battery manufacturing step by examining the battery assembly process, as described in Nelson et al. (2011). Dunn et al. (2012b) identified the dry room step as a major energy consumer, since it incorporates a desiccant wheel with indirect-fired NG reactivation, electric heating, and electric motors. In order to estimate the energy consumption per battery,

Table 49. Li-ion battery production process assumptions

Input or Emission	Unit	Active Material (LMO) Production				Other Battery Material Production						
		Li_2CO_3 Production (Chile)										
		Concentrated Li Brine	Li_2CO_3	Mn_2O_3	$LiMn_2O_4$	Graphite	PVDF (Binder)	$LiPF_6$	Ethylene Carbonate	Dimethyl Carbonate	N-Methyl-2-pyrrolidone (Binder Solvent)	BMS
Input fuel												
Residual oil	MMBtu/ton	–	–	–	–	0.18	0.84	0.37	–	–	–	–
Diesel	MMBtu/ton	0.13	5.99	–	–	–	–	–	–	–	–	–
NG	MMBtu/ton	–	2.26	2.50	13.18	2.02	11.97	–	0.22	1.27	1.73	84.05
Coal	MMBtu/ton	–	–	–	–	0.09	–	–	–	–	–	–
Electricity	MMBtu/ton	–	1.75	0.07	0.02	0.41	8.19	72.64	0.04	0.09	1.02	120.95
Input material												
Soda ash	ton/ton	–	2.48	–	–	–	–	–	–	–	–	–
Concentrated Li brine	ton/ton	–	5.45	–	–	–	–	–	–	–	–	–
Non-combustion emissions												
CO_2	ton/ton	–	–	0.558	0.122	–	–	–	–	–	–	–

electricity and NG consumption for a dry room (1,860 m^2) on an annual basis were obtained from a dry room manufacturer, SCS Systems (Mitchell 2011). Then, the energy consumption was scaled up linearly with the dry room area in BatPaC (3,000 m^2), producing 300 lb of Li-ion battery. The resulting electricity and NG consumption is 0.09 and 0.165 MMBtu/battery, respectively.

Another major energy consumer, identified in Dunn et al. (2012b), is the formation cycling step. Lithium-ion cells are assembled in a discharged state and undergo this step to activate them (Tagawa and Brodd 2009). The first, formation charge activates the active materials and creates the solid electrolyte interphase on the anode. The cell voltage is measured after the first charge, and the battery is left to age for a manufacturer-specific time. Measuring the change in cell voltage before and after formation cycling identifies underperforming cells. The number of cycles that cells undergo after the first formation cycle depends on the manufacturer, but it typically would not exceed two additional cycles (Tagawa and Brodd 2009). Assuming two formation cycles, the formation cycling energy consumption was calculated by multiplying cell capacity and open circuit voltage and accounting for the cycle coulombic and cell efficiency, which results in electricity consumption of 0.06 MMBtu/battery. Dunn et al. (2012b) also estimated that the dry room and cycling steps represent 70% of the energy consumed during manufacturing (Moneypenney 2011). The resulting energy consumption for battery assembly is 0.45 MMBtu/battery.

7.3.6 Other Key Materials Production Pathways

Table 50 provides the key assumptions for production pathways for other key materials: lead, glass, rubber, and copper. Lead is extracted from several minerals, but the main ore is lead sulfite (PbS). In 2004, almost 95% of lead mining took place in Alaska and Missouri, and all the lead concentrates produced from that ore were processed at a smelter-refinery in Missouri (Gabby 2005). Froth flotation is used to separate the lead and other minerals from the waste rock to form a concentrate, which contains between 50% and 60% lead. The concentrate is then sintered before being smelted to produce a 97% lead concentrate, which is then refined by additional smelting to remove further impurities, which produces 99.99% pure lead. Recycled lead production accounted for 88% of the lead domestically produced, with lead acid batteries accounting for 92% of the lead produced from scrap sources (Gabby 2005). Recycled lead smelting and battery recycling are more geographically spread out than mining operations and may occur near population centers. Burnham et al. (2006) estimated energy and material inputs of virgin and recycled lead from Hudson (1981) and Leiby (1993).

Glass is produced by melting raw materials—sand (silica), limestone, soda ash, feldspar (aluminum silicates with potassium, sodium, calcium, or barium), and small quantities of other additives—at a high temperature. The glass for automotive uses is generally produced by means of a float process, in which a thin sheet of glass is formed by flotation on a molten tin bath under a nitrogen atmosphere. The major energy inputs for virgin glass production are NG and electricity at the glass plant (gas for melting and annealing, electricity for forming) and NG for raw material mining and processing. Burnham et al. (2006) estimated total energy consumed in flat glass processing based on Babcock et al. (1988).

Styrene-butadiene rubber (SBR), made from 75% butadiene and 25% styrene (by weight), is used for production of tires and other auto parts, such as gaskets and fan belts. SBR is produced from a cold emulsion process in which butadiene, styrene, soap, water, potassium persulfate catalyst, and a mercaptan regulator are heated in large jacketed reactors to about 50°C. The contents are stirred numerous times, leading to formation of SBR by means of a polymerization process. What results from this reactor is a latex that contains the rubber, which is separated as a fine crumb by treating the latex with a solution of aluminum sulfate or an acidic sodium chloride solution. The crumb is washed, dried in an oven, and then pressed into bales. Burnham et al. (2006) estimated the energy requirement for this production process, almost all of it from oil and gas, from Cuenca et al. (1998).

Table 50. Process assumptions for lead, glass, rubber, and copper

Input or Emission	Unit	Virgin Lead		Recycled Lead Production [a]	Glass Production [a]	Rubber Production[a]	Copper		
		Ore Mining[a]	Virgin Lead Production [a]				Ore Mining[b]	Smelting/ Refining[b]	Drawing Wire[c]
Fuel									
Residual oil	MMBtu/ton	–	–	–	0.42	16.76	–	–	0.84
Diesel	MMBtu/ton	0.49	–	–	–	–	1.03	1.38	–
Natural gas	MMBtu/ton	–	–	–	13.50	16.76	–	8.61	–
Coal	MMBtu/ton	–	–	4.14	–	–	–	3.26	0.01
Electricity	MMBtu/ton	2.10	–	–	0.90	0.34	1.12	6.53	1.63
Coke	ton/ton	–	0.61	–	–	–	–	–	–
Non-combustion emissions									
VOC	ton/ton	–	–	–	–	0.006	–	–	–
CH_4	ton/ton	–	0.004	–	0.004	–	–	–	–
CO_2	ton/ton	–	–	–	0.150	–	–	–	–

[a] Source: Burnham et al. (2006).
[b] Source: Keoleian et al. (2012).
[c] Source: Sullivan et al. (2010).

Copper is smelted or recovered by leaching from dilute sulfide ores found in the southwestern United States. The smelting process leads to significant sulfur oxide emissions, which are captured and converted to sulfuric acid for sale. Because the ores are dilute, significant energy is used for mining and beneficiation (crushing and separating the ore). Energy and material inputs for copper production processes are document in Keoleian et al. (2012), which compiles lifecycle inventory data for metals used in PV production (Fthenakis et al. 2009; 2007).

7.4 Vehicle Assembly, Disposal, and Recycling

Typical vehicle assembly processes include painting; heating, ventilation, and air conditioning (HVAC); material handling; welding; and supply of compressed air. Sullivan et al. (2010) estimated the energy use and emissions associated with these vehicle assembly processes by using data from two sources: painting, HVAC, and material handling from Galitsky and Worrell (2008) and welding from Berry and Fels (1972). Burnham et al. (2006) estimated the electricity required for dismantling vehicles for disposal or recycling to be approximately 1.5 million Btu/vehicle for a vehicle weighing 3,000 lb based on Stodolsky et al. (1995). This value does not include material recovery processes or combustion for energy recovery. GREET includes the energy use of materials associated with material recovery to each specific recycled material. The summary of energy use and non-combustion emissions from vehicle assembly and disposal processes are presented in Table 51.

Table 51. Vehicle assembly, disposal, and recycling process assumptions

Input or Emission	Unit	Vehicle Assembly						Vehicle Disposal and Recycling
		Painting	HVAC & Lighting	Heating	Material Handling	Welding	Compressed Air	
Fuel								
NG	MMBtu/vehicle	2.30	–	2.98	–	–	–	–
Electricity	MMBtu/vehicle	0.46	0.99	–	0.21	0.27	0.41	1.54
Non-combustion emissions								
VOC	ton/vehicle	0.002	–	–	–	–	–	–

7.5 References for Section 7

Aluminum Association, 1998. *Life Cycle Inventory Report for the North American Aluminum Industry*. Washington, DC.

Aluminum Association, 2013. *The Environmental Footprint of Semi-Finished Aluminum Products in North America*. Washington, DC. http://www.aluminum.org/sites/default/files/LCA_Report_Aluminum_Association_12_13.pdf

Argonne National Laboratory, Systems Assessment Group, 2014. *GREET Model, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. https://greet.es.anl.gov/index.php

Babcock, E., A. Elaahi, and H.E. Lowitt, 1988. *The U.S. Glass Industry: An Energy Perspective*. Report DOE/RL/01830-T60, Pacific Northwest Laboratory, Richland, WA.

Berry, R., M.F. and Fels, 1972. *The Production and Consumption of Automobiles*. Illinois Institute for Environmental Quality, Springfield, IL.

Brown, H.L., B.B. Hamel, B.A. Hedman, M. Koluch, B.C. Gajanana, and P. Troy, 1996. *Energy Analysis of 108 Industrial Processes*. The Fairmont Press, Inc.

Burnham, A., M.Q. Wang, and Y. Wu, 2006. *Development and Applications of GREET 2.7 - The Transportation Vehicle-Cycle Model*. Report ANL/ESD/06-5). Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-lkldbrwj

Burnham, A., 2012. *Updated Vehicle Specifications in the GREET Vehicle-Cycle Model*. Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-update-veh-specs

Carlson, E., 2004. TIAX, Cambridge, Mass., Personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, IL.

Cooper, J.S., 2004. *Recyclability of Fuel Cell Power Trains*. Presented at SAE 2006 World Congress, Detroit, MI, doi:10.4271/2004-01-1136. http://dx.doi.org/10.4271/2004-01-1136

Cuenca, R., J. Formento, L. Gaines, B. Marr, D. Santini, M. Wang, S. Adelman, D. Kline, J. Mark, J. Ohi, N. Rau, S. Freeman, K. Humphreys, and M. Placet, 1998. *Total Energy Cycle Assessment of Electric and Conventional Vehicles: An Energy and Environmental Analysis.* Report ANL/ES/RP-96387, Argonne National Laboratory, Argonne, IL. http://dx.doi.org/10.2172/627823

Cuenca, R., 2005. Argonne National Laboratory, Personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, IL.

Deng, L., C.W. Babbitt, and E.D. Williams, 2011. "Economic-balance Hybrid LCA Extended with Uncertainty Analysis: Case Study of a Laptop Computer." *J. Clean. Prod.*, 19, 1198–1206, doi:10.1016/j.jclepro.2011.03.004. http://dx.doi.org/10.1016/j.jclepro.2011.03.004

Dunn, J., L. Gaines, M. Barnes, J. Sullivan, and M. Wang, 2012b. *Material and Energy Flows in the Materials Production, Assembly, and End of Life Stages of the Automotive Lithium Ion Battery Life Cycle.* Report ANL/ESD/12-3, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-lib-lca

Dunn, J., L. Gaines, M. Barnes, J. Sullivan, and M. Wang, 2014b. *Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle.* Report ANL/ESD/12-3, Rev., Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-li-ion

Dunn, J., L. Gaines, J.C. Kelly, C. James, and K.G. Gallagher, 2014c. "The Significance of Li-ion Batteries in Electric Vehicle Life-cycle Energy and Emissions and Recycling's Role in its Reduction." *Energy Environ. Sci*., 8, 158–168, doi:10.1039/C4EE03029J. http://dx.doi.org/10.1039/C4EE03029J

Dunn, J., C. James, L. Gaines, K. Gallagher, Q. Dai, and J.C. Kelly, 2015. *Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries*. Report ANL/ESD-14/10, Rev., Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-anode-cathode-liion

Espinosa, N., R. García-Valverde, and F.C. Krebs, 2011. "Life-cycle Analysis of Product Integrated Polymer Solar Cells." *Energy Environ. Sci*., 4, 1547–1557, doi:10.1039/C1EE01127H. http://dx.doi.org/10.1039/C1EE01127H

Franklin Associates, 2001. *A Life Cycle Inventory of Selected Commercial Roofing Products*. Athena™ Sustainable Materials Institute, Ottawa, ON, Canada. http://www.athenasmi.org/wp-content/uploads/2011/10/4_Commercial_Roofing_Products.pdf

Franklin Associates, 2011. *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*. American Chemistry Council (ACC), Plastics Division, Washington, DC. http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only

Fthenakis, V., W. Wang, and H.C. Kim, 2007. *Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics* Report BNL-77919-2007, Brookhaven National Laboratory, Upton, NY. http://dx.doi.org/10.2172/909957

Fthenakis, V., W. Wang, and H.C. Kim, 2009. "Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics." *Renew. Sustain. Energy Rev*., 13, 493–517, doi:10.1016/j.rser.2007.11.012. http://dx.doi.org/10.1016/j.rser.2007.11.012

Gabby, P., 2005. *United States Geological Survey Mineral Yearbook*. U.S. Geological Survey, Washington, DC.

Galitsky, C., and E. Worrell, 2008. *Energy Efficiency Improvement and Cost Saving Opportunities for the Vehicle Assembly Industry*. Report LBNL-50939-Revision, Lawrence Berkeley National Laboratory, Berkeley, CA. http://dx.doi.org/10.2172/927881

Glauser, J., and Y. Inoguchi, 2011. *Lithium, Lithium Minerals, and Lithium Chemicals.* CEH Marketing Research Report, SRI Consulting, Zurich, Switzerland.

Gruber, P.W., P.A. Medina, G.A. Keoleian, S.E. Kesler, M.P. Everson, and T.J. Wallington, 2011. "Global Lithium Availability." *J. Ind. Ecol.*, 15, 760–775, doi:10.1111/j.1530-9290.2011.00359.x. http://dx.doi.org/10.1111/j.1530-9290.2011.00359.x

Hudson, C.L., 1981. *Energy Requirements for Materials Used in Vehicles Characterized for the TAPCUT Project*. Report ANL/EES-TM-211, Argonne National Laboratory, Argonne, IL.

IEA (International Energy Agency), 2012. *Electricity/Heat in Chile in 2009*. Electr. Chile 2009. http://www.iea.org/statistics/statisticssearch/report/?country=CHILE&product=electricityandheat&year=2009

James, B.D., J.M. Moton, and W.G. Colella, 2014. *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2014 Update*. Strategic Analysis Inc., Arlington, VA.

Keoleian, G., S. Miller, R. De Kleine, A. Fang, and J. Mosley, 2012. *Life Cycle Material Data Update for GREET Model* Report CSS12-12, University of Michigan, Ann Arbor, MI. https://greet.es.anl.gov/publication-greet2-lca-update

Leiby, R., 1993. *Secondary Smelting at East Penn Manufacturing*. Presented at the Fifth International Seminar on Battery Waste Management, Deerfield Beach, FL.

Markus Engineering Services, 2002. *Cradle-to-gate Life Cycle Inventory: Canadian and US Steel Production by Mill Type*. Athena™ Sustainable Materials Institute, Ottawa, ON, Canada. http://www.athenasmi.org/wp-content/uploads/2011/10/1_Steel_Production.pdf

Mitchell, J., 2011. SCS Systems, Houston, TX, Personal communication with Jennifer Dunn, Argonne National Laboratory, Argonne, IL.

Moawad, A., P. Sharer, and A. Rousseau, 2011. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*. Report ANL/ESD/11-4, Argonne National Laboratory, Argonne, IL. http://www.anl.gov/energy-systems/publication/light-duty-vehicle-fuel-consumption-displacement-potential-2045

Moneypenney, B., 2011. Dow Kokam, Midland, MI, Personal communication with Jennifer Dunn, Argonne National Laboratory, Argonne, IL.

Muir, R., 2005. United States Council for Automotive Research/Vehicle Recycling Partnership (USCAR/VRP), Southfield, Mich., Personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, IL.

Nelson, P.A., K.G. Gallagher, I. Bloom, and D.W. Dees, 2011. *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles*. Report ANL-11/32, Argonne National Laboratory, Argonne, IL. http://dx.doi.org/10.2172/1027714

Notter, D.A., M. Gauch, R. Widmer, P. Wäger, A. Stamp, R. Zah, and H.-J. Althaus, 2010. "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles." *Environ. Sci. Technol*., 44, 6550–6556, doi:10.1021/es903729a. http://dx.doi.org/10.1021/es903729a

PE Americas, 2010. *Life Cycle Impact Assessment of Aluminum Beverage Cans*. Aluminum Association, Inc., Washington, DC. http://www.container-recycling.org/assets/pdfs/aluminum/LCA-2010-AluminumAssoc.pdf

Plastics Europe, 2010. *Eco-Profiles*. http://www.plasticseurope.org/plasticssustainability/eco-profiles.aspx

SQM, 2001. Capitulo 2 Descripcion del Proyecto. Capitulo 2 Descripcion Proy. http://seia.sea.gob.cl/expediente/expedientesEvaluacion.php?modo=ficha&id_expediente=3521#-1

Stodolsky, F., A. Vyas, R. Cuenca, and L. Gaines, 1995. *Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles*. Presented at the 1995 Total Life Cycle Conference & Exposition, Vienna, Austria.

Sullivan, J.L., R.L. Williams, S. Yester, E. Cobas-Flores, S.T. Chubbs, S.G. Hentges, and S.D. Pomper, 1998. *Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project.* SAE Technical Paper 982160, Warrendale, PA. http://papers.sae.org/982160/

Sullivan, J., A. Burnham, and M. Wang, 2010. *Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing*, Report ANL/ESD/10-6, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-vehicle_and_components_manufacturing

Sutter, J., 2007. *Life Cycle Inventories of Petrochemical Solvents*. Swiss Centre for Life Cycle Inventories, Zurich, Switzerland.

Tagawa, K., and R.J. Brodd, 2009. "Production Processes for Fabrication of Lithium-Ion Batteries." In: M. Yoshio, R.J. Brodd, and A. Kozawa, A. (eds.), *Lithium-Ion Batteries Science and Technologie*s, Springer, New York, NY.

8 CRADLE-TO-GRAVE GHG RESULTS AND SENSITIVITY

8.1 GREENHOUSE GAS EMISSIONS

The C2G GHG emissions (g CO_2e/mi) and energy use (Btu/mi) calculated for the vehicle-fuel combinations investigated in this study are given in Tables 52 and 53 and are plotted in Figures 19–21. The assumptions behind the vehicle-fuel combinations in this section are discussed in greater detail in Sections 4–7. GTL FTD is examined in Sections 4.5 and 5.4, CNG is examined in Sections 4.2 and 5.2, LPG is examined in Sections 4.1 and 5.2, biofuels in flexible fuel vehicles (FFVs) are examined in Sections 4.3 and 5.3–5.5, and H_2 pathways are examined in Sections 4.4 and 5.7. The vehicles considered are ICEVs, HEVs, PHEVs, H_2 FCEVs, and BEVs. Advanced electricity generation pathways considered for electrification of vehicles include ACC NG generation and CCS, examined in Sections 4.6 and 5.6. A sensitivity analysis for these pathways is presented in Appendix D.

Figure 19 shows results for the fuel production pathways and vehicle technologies. The "CURRENT TECHNOLOGY" cases evaluate current fuel production and vehicle technologies using current feedstock sources and process fuel mixes, while the "FUTURE TECHNOLOGY" cases represent low-carbon pathways. Figure 19 should be read as follows:

- Black line: CURRENT TECHNOLOGY. Both the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases are assumed to have the same GHG emissions.
- Red line: Potential future vehicle efficiency gains. Fuel economy improvement estimates are based on adoption of advanced vehicle and powertrain technologies in the 2025–2030 timeframe. For electric vehicles, this line corresponds to the AEO 2015 electricity mix in a vehicle with future technology gains (EIA 2015a).
- Down-arrows: Potential GHG reductions from low-carbon fuels and electricity in addition to vehicle efficiency gains.

For instance, for the gasoline ICEV pathway, the potential vehicle efficiency gains would bring emissions down from 457 g CO_2e/mi to 352 g CO_2e/mi; these emissions could be further reduced using a low-carbon fuel to about142 g CO_2e/mi under the right conditions.

The results show that by combining vehicle gains with low-carbon fuels, GHG emission reductions more than double in most cases compared to vehicle gains alone. Note that the down-arrows show a plausible reduction of the carbon footprint of the vehicle-fuel pathway, but the cost and feasibility of achieving the indicated GHG emission reductions were not considered.

In general, it is clear from Figure 19 that large GHG reductions for LDVs are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation. Achieving a net lifecycle reduction in GHG emissions is a challenging task and must overcome both technological hurdles as well as cost and market acceptance constraints. Section 3.3 discusses the TRLs of various pathways.

Figure 20 illustrates sensitivities of the resulting GHG emissions to other estimates of LUC. For the corn E85 pathway, studies conducted between 2008 and 2014 have calculated values ranging from ~350 to 675 g CO_2e/mi. The value used for corn E85 in this study is based on the LUC calculated by CCLUB (7.6 g CO_2/MJ of ethanol), as discussed in Section 4.3.4. There are fewer cases in the literature showing the possible range of GHG emission contributions from LUC from soybean cultivation for the production of HRD and FAME; Figure 20 demonstrates how adding these contributions to the calculations would

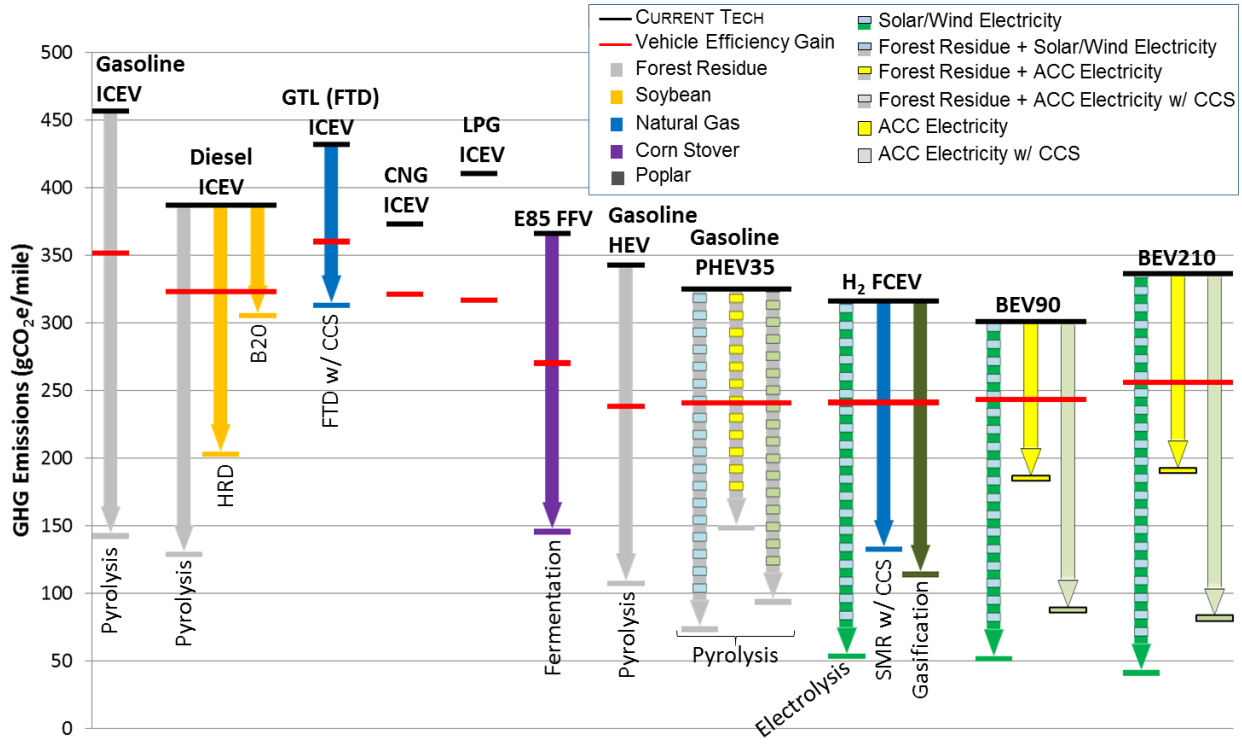

Figure 19. Potential GHG emissions reductions. The values associated with this chart are given in Table 52.

result in an additional ~100 g CO_2e/mi for HRD and approximately 10 g CO_2e/mi for B20.[14] These differentials demonstrate that although the scientific community does not have a consensus on LUC calculation methodologies and assumptions, it should not be ignored; rather, studies should include sensitivities to LUC assumptions.

8.2 TOTAL ENERGY

Figure 21 shows the amount of energy (Btu/mi) by source needed to produce the vehicles and fuels in the study. The pathways for the CURRENT TECHNOLOGY case rely more heavily on petroleum and NG; the FUTURE TECHNOLOGY low-carbon cases, while still heavily relying on NG, also have a greater reliance on biomass and other renewable energy sources. Values for Figure 21 are shown in Table 53.

8.3 REFERENCES FOR SECTION 8

ATLASS Consortium, 2011. *Assessing the Land Use Change Consequences of European Biofuel Policies*. http://trade.ec.europa.eu/doclib/html/148289.htm

CARB (California Air Resources Board), 2015. *Low Carbon Fuel Standard Regulation*. http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

[14] B20 corresponds to a mix of 20% FAME and 80% conventional diesel.

Table 52. GHG emissions for the FUTURE TECHNOLOGY reductions shown in Figure 19 (g CO_2e/mile)

Pathway	Gasoline ICEV	Diesel ICEV	GTL (FTD)	CNG ICEV	LPG ICEV	E85 FFV	Gasoline HEV	Gasoline PHEV10	Gasoline PHEV35	H_2 FCEV	BEV90	BEV210
CURRENT TECHNOLOGY	457	387	432	373	410	366	343	337	325	316	301	336
Vehicle efficiency gain	352	323	360	321	317	270	238	244	241	241	243	256
Forest residue pyrolysis	142	128	–	–	–	–	107	–	–	–	–	–
Soybean	–	203/ 305	–	–	–	–	–	–	–	–	–	–
NG	–	–	313	–	–	–	–	–	–	132	–	–
Corn stover	–	–	–	–	–	145	–	–	–	–	–	–
Solar/wind electricity	–	–	–	–	–	–	–	–	–	53	52	41
Pyrolysis + solar/wind	–	–	–	–	–	–	–	98	73	–	–	–
Pyrolysis + ACC electricity	–	–	–	–	–	–	–	121	148	–	–	–
Pyrolysis + ACC electricity with CCS	–	–	–	–	–	–	–	104	94	–	–	–
ACC electricity	–	–	–	–	–	–	–	–	–	–	185	191
ACC electricity with CCS	–	–	–	–	–	–	–	–	–	–	88	81
Poplar	–	–	–	–	–	–	–	–	–	114	–	–

EIA (U.S. Energy Information Administration), 2015a. *Annual Energy Outlook 2015 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

Elliott, J., B. Sharma, N. Best, M. Glotter, J.B. Dunn, I. Foster, F. Miguez, S. Mueller, and M. Wang, 2014. "A Spatial Modeling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions." *Environ. Sci. Technol*., 2014, 48 (4), pp. 2488–2496, DOI: 10.1021/es404546r. http://pubs.acs.org/doi/abs/10.1021/es404546r

EPA (U.S. Environmental Protection Agency), 2010c. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. Report EPA-420-R-10-006. http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen, 2010. "Effects of US Maize Ethanol in Global Land Use and Greenhouse Gas Emissions: Estimating Market-Mediated Responses." *Bioscience*, 60:223e31.

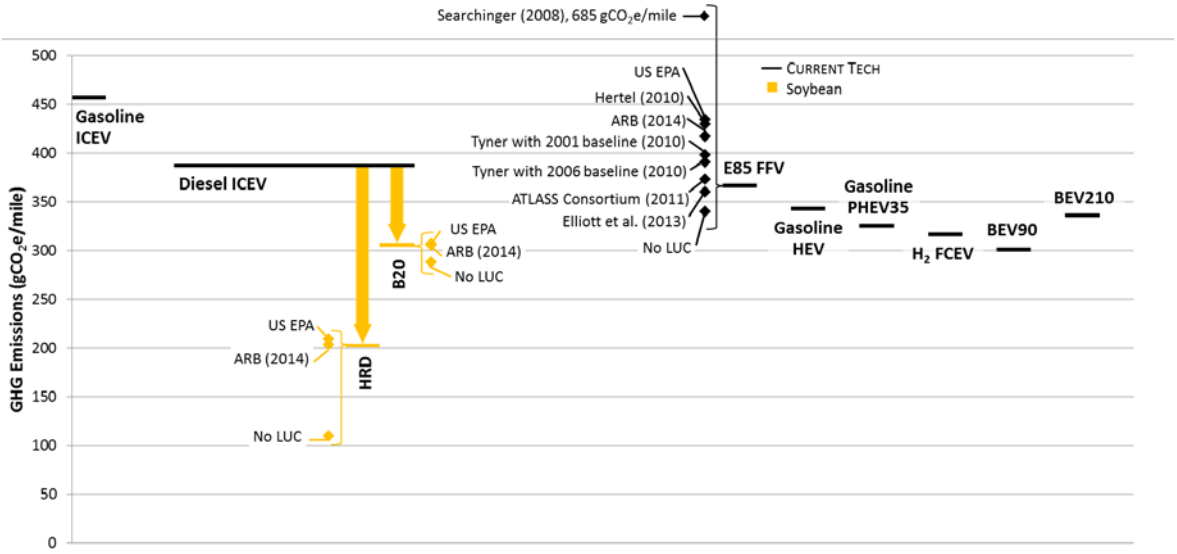

Figure 20. GHG emissions for biomass-based fuels

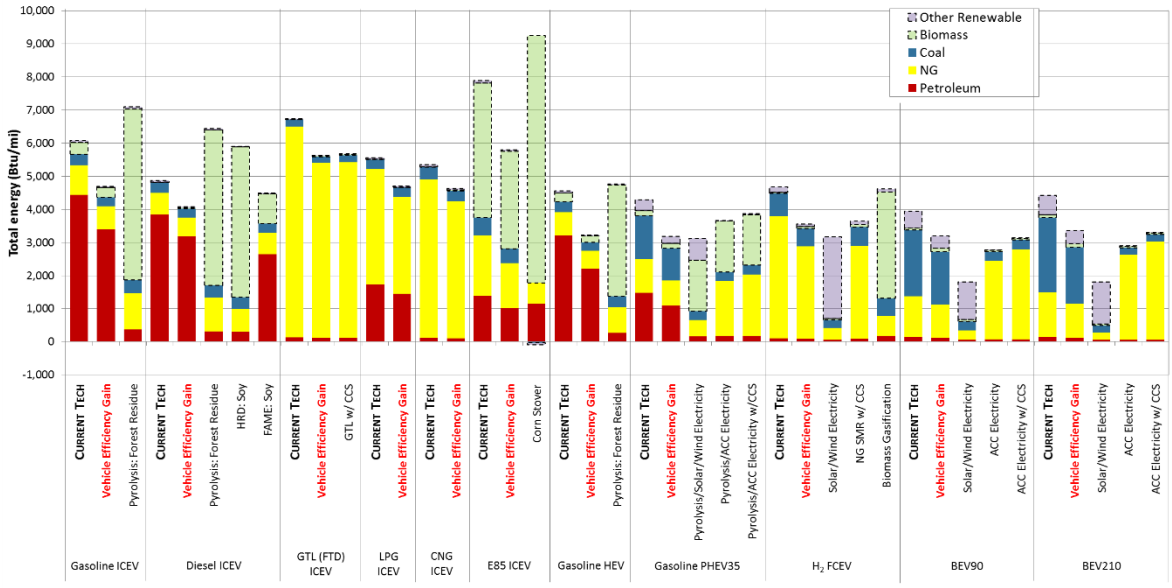

Figure 21. GREET results of energy consumption for all vehicle-fuel combinations (Btu/mi). Each bar is segmented by energy source. Data for this figure are in Table 53.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu, 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change." *Science*, 319(5867), pp. 1238–1240, DOI: 10.1126/science.1151861. http://science.sciencemag.org/content/319/5867/1238.abstract

Tyner, W.E., F. Taheripour, Q. Zhuang, D. Birur, and U. Baldos, 2010. *Land Use Changes and Consequent CO_2 Emissions Due to US Corn Ethanol Production: A Comprehensive Analysis*. Purdue University, Department of Agricultural Economics. https://www.gtap.agecon.purdue.edu/resources/download/5200.pdf

Table 53. Total energy consumed, as shown in Figure 21 (Btu/mi)

Fuel	Gasoline ICEV			Diesel ICEV					GTL FTD ICEV			LPG ICEV	
	Current Tech	Vehicle Efficiency Gains	Forest Residue Pyrolysis	Current Tech	Vehicle Efficiency Gains	Forest Residue Pyrolysis	HRD from Soybeans	FAME from Soybeans	Current Tech	Vehicle Efficiency Gains	GTL w/ CCS	Current Tech	Vehicle Efficiency Gains
Petroleum	4,443	3,385	372	3,839	3,189	318	303	2,645	125	115	116	1,73	1,451
NG	890	708	1,095	665	569	1,016	679	642	6,376	5,297	5,309	3,48	2,924
Coal	335	277	394	304	259	372	366	283	212	185	205	289	281
Biomass	360	301	5,182	7	34	4,690	4,535	907	3	30	31	6	6
Other renewables	61	26	59	54	21	51	29	24	29	1	7	50	48

Fuel	CNG ICEV		E85 ICEV			Gasoline HEV			H_2 FCEV				
	Current Tech	Vehicle Efficiency Gains	Current Tech	Vehicle Efficiency Gains	Corn Stover	Current Tech	Vehicle Efficiency Gains	Forest Residue Pyrolysis	Current Tech	Vehicle Efficiency Gains	Solar/wind electricity	NG SMR w/ CCS	Biomass Gasification
Petroleum	113	105	1,387	1,022	1,149	3,207	2,209	264	105	85	64	85	171
NG	4,795	4,140	1,827	1,361	630	712	534	784	3,684	2,797	350	2,816	604
Coal	369	313	540	421	-31	317	253	328	698	535	242	568	539
Biomass	9	36	4,059	2,958	7,481	260	207	3,357	22	59	48	74	3,213
Other renewables	70	35	85	43	-56	57	20	41	165	88	2,461	97	89

Fuel	Gasoline PHEV10					Gasoline PHEV35				
	Current Tech	Vehicle Efficiency Gains	Pyrolysis w/ Solar/Wind Electr.	Pyrolysis w/ ACC Electr.	Pyrolysis w/ ACC Electr. w/ CCS	Current Tech	Vehicle Efficiency Gains	Pyrolysis w/ Solar/Wind Electr.	Pyrolysis w/ ACC Electr.	Pyrolysis w/ ACC Electr. w/ CCS
Petroleum	2,707	1,920	238	239	239	1,476	1,087	167	172	172
NG	798	601	701	1,058	1,119	1,014	767	482	1,659	1,860
Coal	605	453	313	314	314	1,323	977	275	277	277
Biomass	229	192	2,862	2,862	2,862	154	148	1,536	1,536	1,536
Other renewables	135	72	230	36	36	329	209	662	24	24

Fuel	BEV90					BEV210				
	Current Tech	Vehicle Efficiency Gains	Solar/ Wind Electr.	ACC Electr.	ACC Electr. w/ CCS	Current Tech	Vehicle Efficiency Gains	Solar/ Wind Electr.	ACC Electr.	ACC Electr. w/ CCS
Petroleum	144	116	61	69	70	154	115	53	62	64
NG	1,228	1,004	286	2,374	2,730	1,340	1,029	224	2,567	2,966
Coal	2,000	1,606	268	271	272	2,257	1,712	211	215	215
Biomass	72	103	50	51	51	83	104	45	45	46
Other renewables	506	365	1,144	12	12	588	406	1,279	9	10

9 LEVELIZED COST OF DRIVING ANALYSIS

The fuel cost data from Section 5 and the vehicle cost and fuel economy data from Section 6 were used to develop a LCD metric. The LCD framework enables a comparison of vehicle costs and respective fuel economy and associated fuel costs on the same basis. LCD costs for the various vehicle-fuel pathways can be compared to better understand the ownership costs of the vehicle-fuel platforms relative to one another and relative to a baseline gasoline ICEV.

9.1 LCD ANALYSIS FRAMEWORK

In this study, the LCD is defined as the sum of the amortized net vehicle cost per mile (LCD_{veh}) and the fuel cost component (LCD_{fuel}): $LCD = LCD_{veh} + LCD_{fuel}$. LCD has units of dollars per mile driven. The LCD calculation does not consider ownership costs other than vehicle or fuel (e.g., insurance, maintenance). The LCD is a function of vehicle purchase cost, assumed vehicle residual value at the end of the analysis period, assumed discount rate, fuel costs, fuel efficiency, and assumed VMT. Costs in this study are considered in real dollars (2013$), not nominal dollars, and thus any future inflation rate has been factored out of the analysis.

Fuel costs (discussed in Section 5) are assumed to remain constant in real dollar terms from the time of the vehicle purchase through the end of the analysis period. Thus, the fuel cost component of LCD can be calculated directly as the fuel cost (in 2013$/gge) divided by the vehicle fuel economy (in mpgge).

The vehicle cost component of the LCD is derived from the net vehicle cost to the owner, which is defined as the initial purchase cost of the vehicle (Section 6) less the residual value at the end of the analysis period. Since the residual value is returned to the vehicle buyer after a number of years, it must be discounted to place it on a comparable basis with the initial vehicle purchase cost. Once it is discounted, it may then be subtracted from the initial vehicle purchase cost to arrive at a net vehicle cost. The vehicle cost component of the LCD is computed by allocating the net vehicle cost uniformly over the VMT and applying the assumed discount rate to reflect the years in which miles are driven. More specifically, the vehicle cost component of the LCD is found by solving the following equation:

$$Vehicle\ Cost\ (net) = \sum_{i=1}^{t} \frac{LCD_{veh} * VMT_i}{(1+D)^i} \tag{3}$$

where LCD_{veh} represents the vehicle component of the LCD metric (expressed in $/mile driven), t is the time period in years, VMT_i is the number of miles driven in year i, D is the discount rate expressed as an annual percentage, and $(1 + D)^i$ is the discount factor applied in year i. The fuel cost component of the LCD (LCD_{fuel}) is calculated as follows:

$$LCD_{fuel} = \frac{FuelPrice}{FuelEconomy} \tag{4}$$

As noted, the LCD metric depends on an assumption of annual VMT. The VMT assumption in this calculation is based on NHTSA's passenger car travel mileage schedule (NHTSA 2006), which estimates the average annual miles traveled by passenger cars in the U.S. for each year of a vehicle's life. In that schedule, a new vehicle travels 14,231 mi in its first year, and travel decreases to 9,249 mi in year 15, the assumed vehicle EOL in this analysis. The total number of miles traveled over a vehicle's lifetime is 178,102. It is important to note that the BEV90 is assumed to cover only 70% of the VMT of the other vehicles in this study, based on indications from Idaho National Laboratory's "EV Project," in which data

collected on a large number of vehicles showed that BEVs with short range (e.g., less than 100 mi), on average, traveled roughly 30% fewer miles than conventional vehicles (Francfort et al. 2015).

A discount rate is applied to equate capital cash flows that occur at different points in time, i.e., the initial vehicle purchase price and the residual value after *t* years. In this analysis, a discount rate of 5% is assumed, with a low and high sensitivity at 3% and 7%, respectively. This discount rate, applied to consumer cash flow, is in real terms and excludes inflation (as noted above, all inflation has been factored out of the analysis).

In the study, we consider three time periods: 3, 5, and 15 years. Typically, 3–5 years is used as a payback period (both 3 and 5 years are considered) and 15 years is an appropriate estimate of a passenger vehicle's lifetime, such that a 15-year analysis offers a societal perspective on total lifetime emissions and total lifetime cost. The shorter time periods capture the perspective of the typical first-purchaser. The longer time period, chosen to cover the entire life of the vehicle, provides a societal perspective. Both perspectives are important in comparing different vehicle-fuel technology combinations.

Data published in the Automotive Lease Guide for the depreciation of midsize vehicles indicate a depreciation rate in the range of approximately 15–20% over the first 3–9 years. In this study, we use the midpoint in this range, or 17.5% per year. In the absence of any information to the contrary, and for simplicity, we assumed the same depreciation rate for all vehicle technologies. Appendix E illustrates how the LCD calculations were performed.

9.2 LCD RESULTS

Using the analysis framework described above, LCD estimates were developed for all vehicle-fuel pathways for both the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases. All costs are presented in 2013$. Considering baseline, high, and low vehicle and fuel cost estimates, as well as different analysis periods and discount rates, a large number of LCD permutations are possible. To illustrate LCD results for the vehicle-fuel pathways, a base case was developed for the CURRENT TECHNOLOGY, HIGH VOLUME (MY2015) and FUTURE TECHNOLOGY, HIGH VOLUME cases (MY2025–2030) using the base case vehicle and fuel costs over a 5-year analysis period using a 5% discount rate. Results of this illustrative base case are shown in Figures 22 and 23.

As seen in the figures, for all vehicle-fuel pathways, the vehicle cost (less residual value) represents a significant portion of the total LCD. For the CURRENT TECHNOLOGY, HIGH VOLUME case, the more commercially established vehicles (gasoline, diesel, E85, CNG, LPG, and HEV) have LCDs below $0.40/mi driven. Emerging vehicle technologies, such as BEVs, longer-range PHEVs, and FCEVs have LCDs exceeding $0.50/mi. As shown in the FUTURE TECHNOLOGY, HIGH VOLUME case, improvements in technology and cost are expected to reduce the cost of driving to below $0.45/mi for all vehicle platforms except BEVs.

The C2G study uses a range of estimates for vehicle and fuel costs for the CURRENT TECHNOLOGY, HIGH VOLUME case. The resulting LCD results based on these high and low fuel and vehicle cost ranges are shown as uncertainty bars in Figure 22. Additionally, as described in Section 5.7, a CURRENT TECHNOLOGY, LOW VOLUME cost estimate was developed for hydrogen fuel to better understand the impact of hydrogen fuel cost in the near term, shown as a green diamond. Figure 23 shows the additional per-mile cost associated with this low-volume hydrogen fuel. For FCEVs in the CURRENT TECHNOLOGY case, the low-volume cost of hydrogen increases the FCEV LCD from $0.54/mi to $0.62/mi.

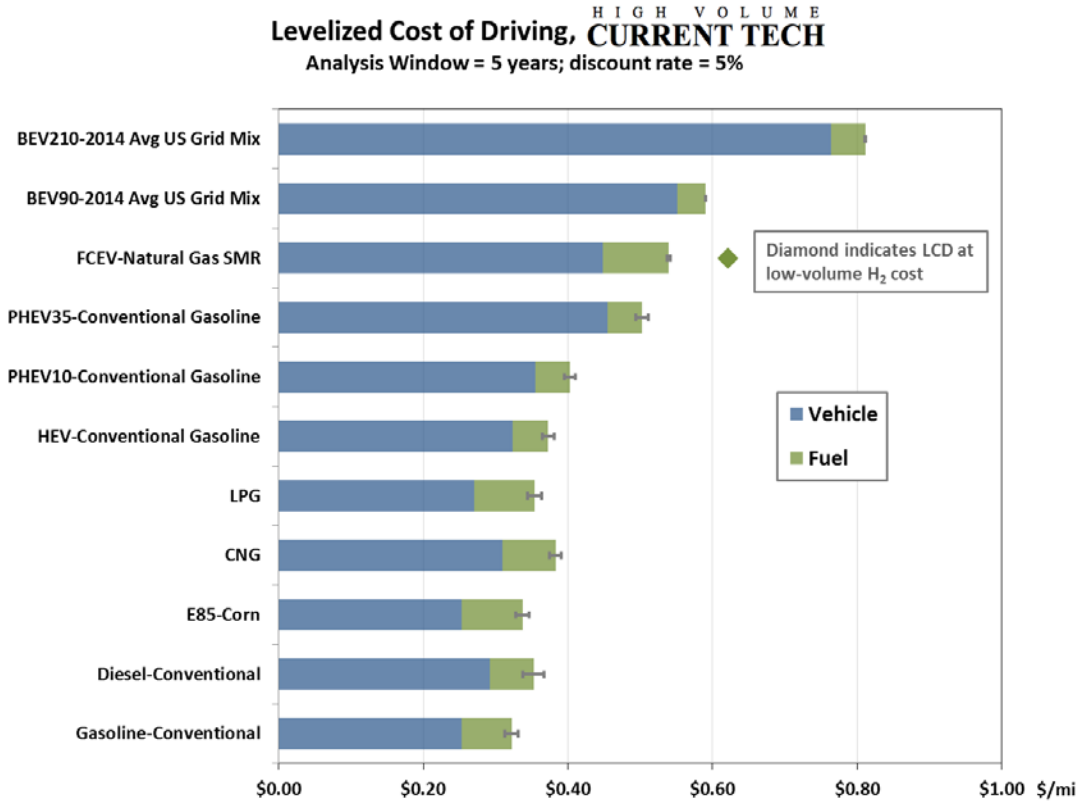

Figure 22. LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case

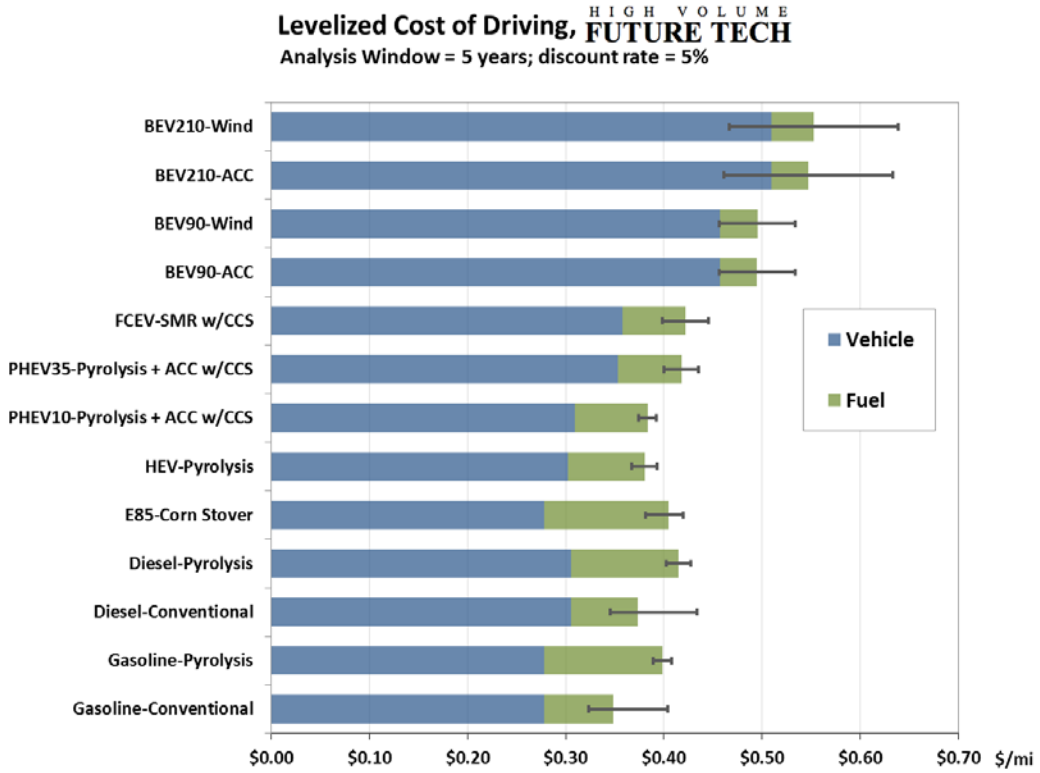

Figure 23. LCD by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case

As described in Sections 5 and 6, vehicle and fuel cost ranges were developed for the FUTURE TECHNOLOGY, HIGH VOLUME case. The uncertainty bars in Figure 23 show the range of LCD results for each vehicle-fuel pathway (evaluated over a 5-year ownership period using a 5% discount rate) if the low and high cost estimates are used for the vehicle and fuel costs for the pathway.

9.3 LCD SENSITIVITY RESULTS

In addition to the illustrative base case, sensitivity analyses of the LCD for the various vehicle-fuel pathways were conducted for both the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases. As with the baseline LCD analysis, the 3-year and 15-year LCD analysis used the base case vehicle and fuel costs and a discount rate of 5%. The results of the 3-year and 15-year LCD analyses for the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases are shown in Figures 24 and 25, respectively.

To better understand the full range of potential LCD results, sensitivity analyses were conducted to develop upper- and lower-bound LCD estimates for each vehicle-fuel pathway for both the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases. The upper-bound LCD estimates for the CURRENT TECHNOLOGY, HIGH VOLUME case were based on a 3-year ownership period using a 7% discount rate. The lower-bound LCD estimates were based on a 15-year ownership period using a 3% discount rate. For both the upper- and lower-bound LCD estimates (and the base case estimates), the base case vehicle and fuel costs were used. The results for the CURRENT TECHNOLOGY, HIGH VOLUME case are shown in Figure 26.[15]

Upper- and lower-bound LCD estimates were made for the FUTURE TECHNOLOGY, HIGH VOLUME case as well. As with the CURRENT TECHNOLOGY, HIGH VOLUME case, the upper-bound LCD estimate for the FUTURE TECHNOLOGY, HIGH VOLUME case assumes a 3-year ownership period using a 7% discount rate. However, for the FUTURE TECHNOLOGY, HIGH VOLUME upper-bound estimates, costs were based on the high vehicle and fuel cost estimates for each pathway (or base case fuel cost if a high fuel cost was not available). Similarly, the lower-bound LCD estimate for the FUTURE TECHNOLOGY, HIGH VOLUME case was based on a 15-year ownership period and 3% discount rate, using low cost estimates for vehicles and fuel. The upper- and lower-bound LCD estimates for each vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case (along with the base case results) are shown in Figure 27.

In addition to the sensitivity cases investigating the effects of discount rates, analysis period, and vehicle and fuel costs, a low-volume sensitivity analysis was conducted to investigate the effect on the LCD metric of the cost of vehicles and fuel in the early commercialization period. Based on the low-volume vehicle costs (discussed in Section 6.5) for CNG ICEVs, PHEVs, FCEVs, and BEVs, as well as the low-volume cost of hydrogen fuel (discussed in Section 5), the LCD for these early market vehicles was analyzed, with the results shown in Figure 28 for the 5-year analysis window, 5% discount rate base case, and shown in Figure 29 for the 15-year vehicle lifetime, 5% discount rate case.

[15] Figure 26 includes uncertainty bars to depict the uncertainty due to analyzing high and low vehicle and fuel costs, but since the high-low range of costs is very tight (due to more certain costs in the CURRENT TECHNOLOGY, HIGH VOLUME case), the uncertainty bars are masked by the diamond markers for the base case.

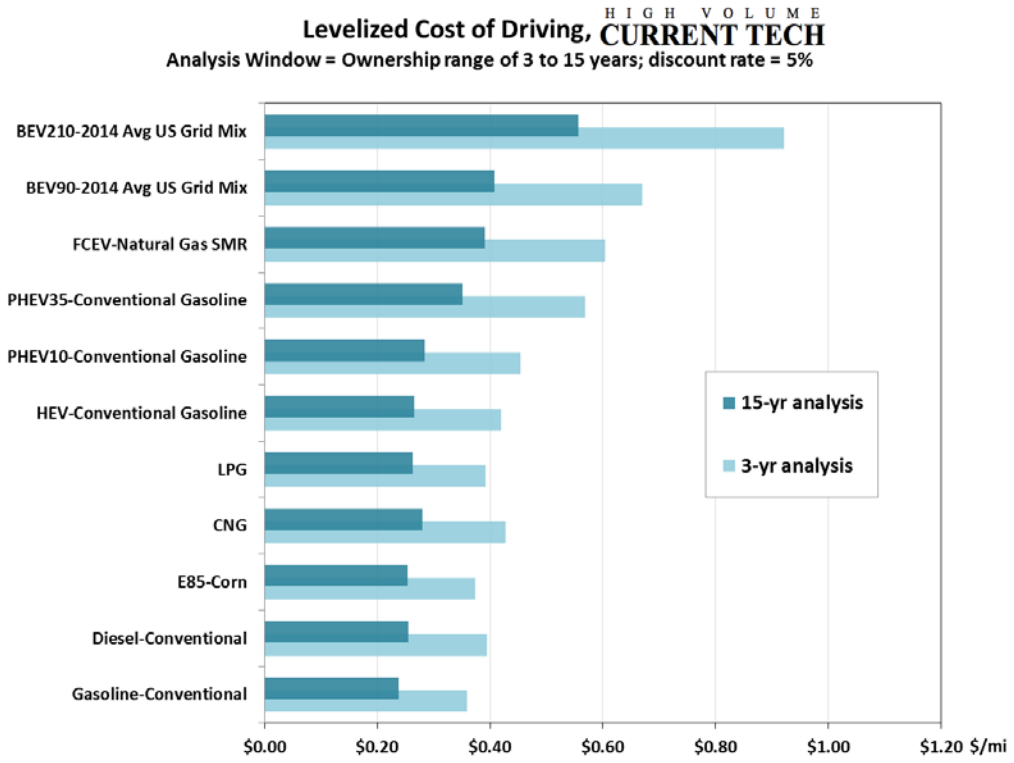

Figure 24. 3-year and 15-year LCD results by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case

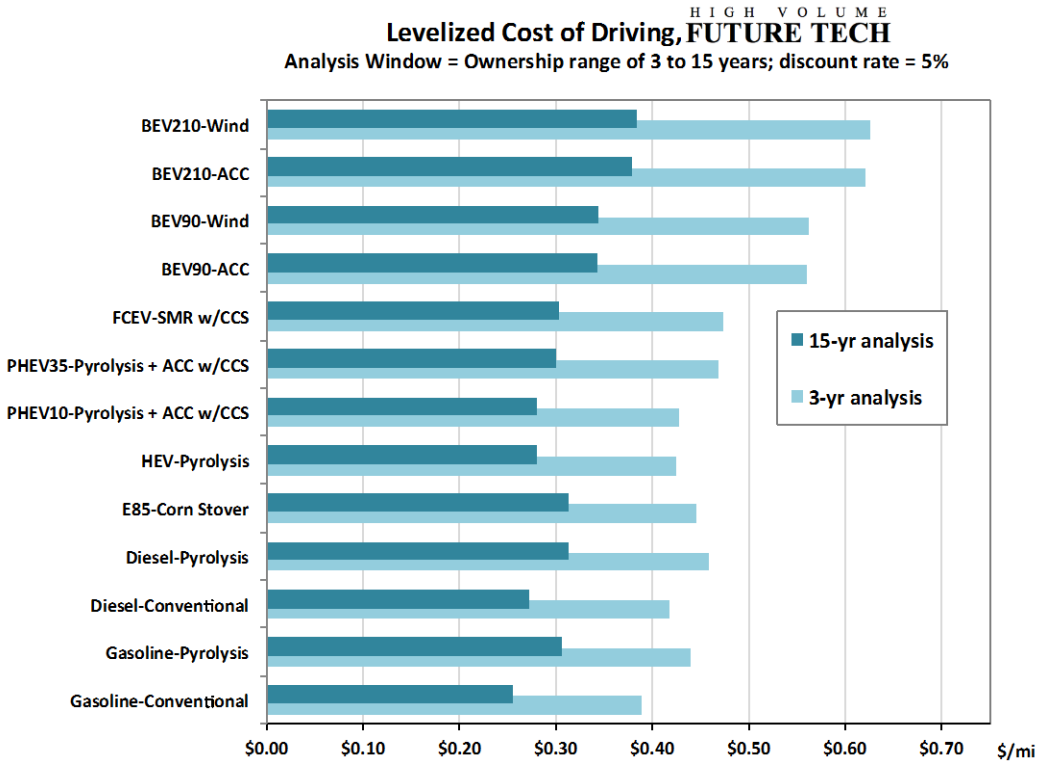

Figure 25. 3-year and 15-year LCD results by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case

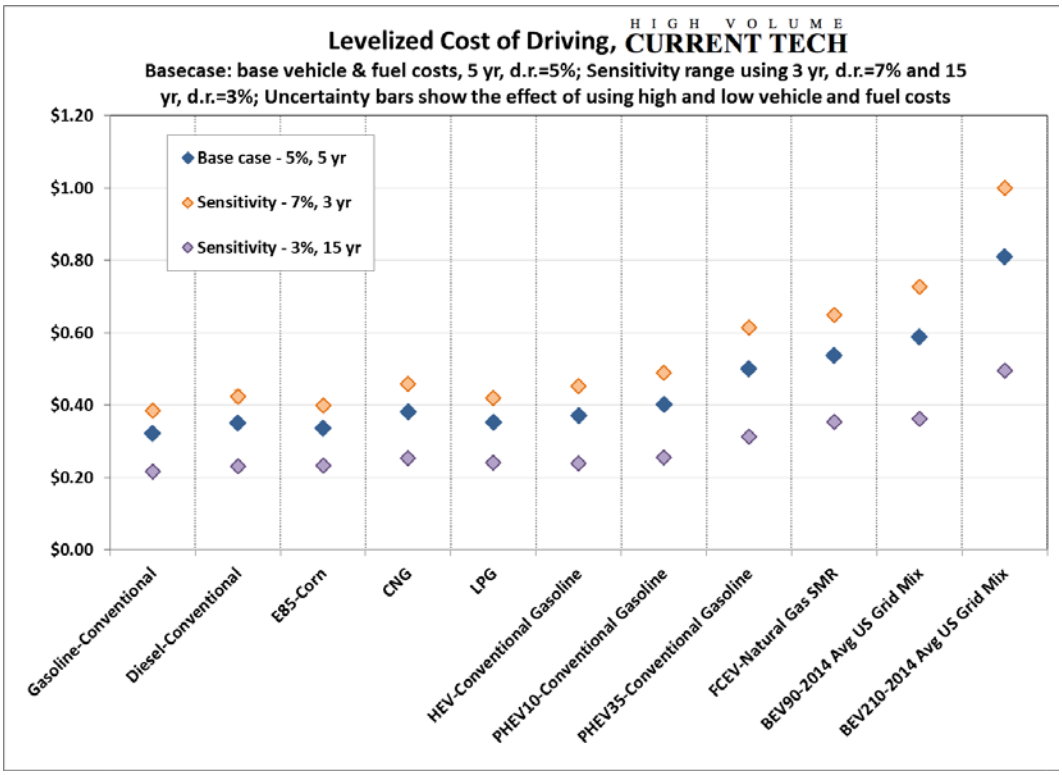

Figure 26. Upper- and lower-bound LCD results by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case

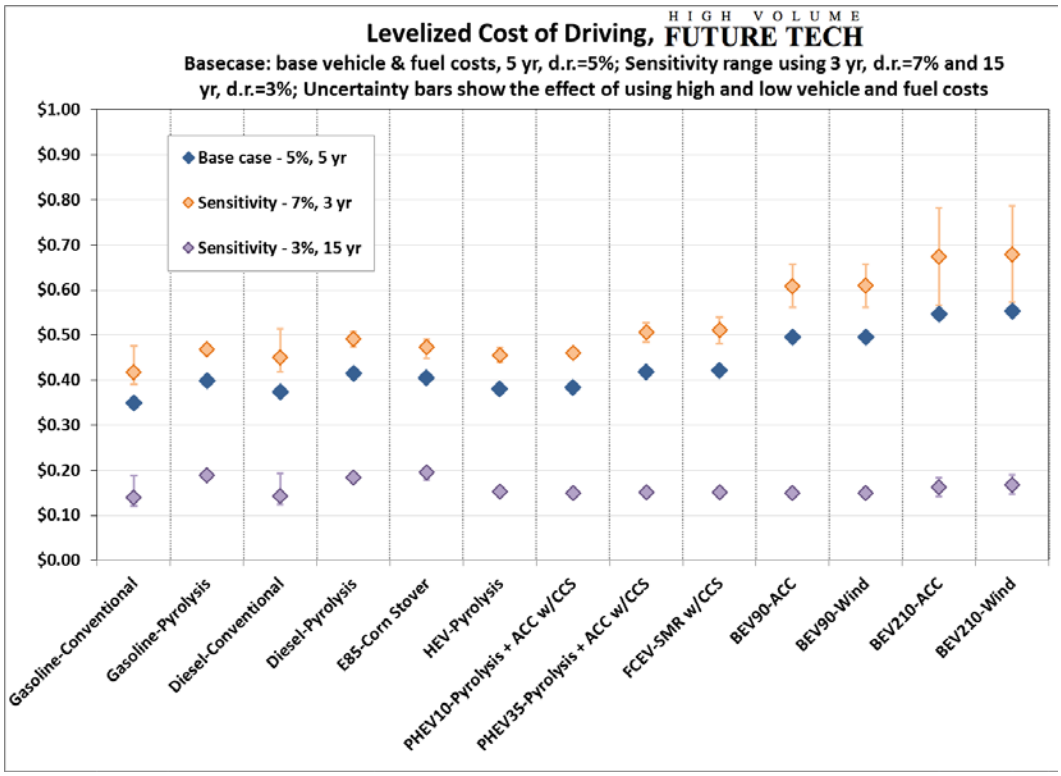

Figure 27. Upper- and lower-bound LCD results by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case

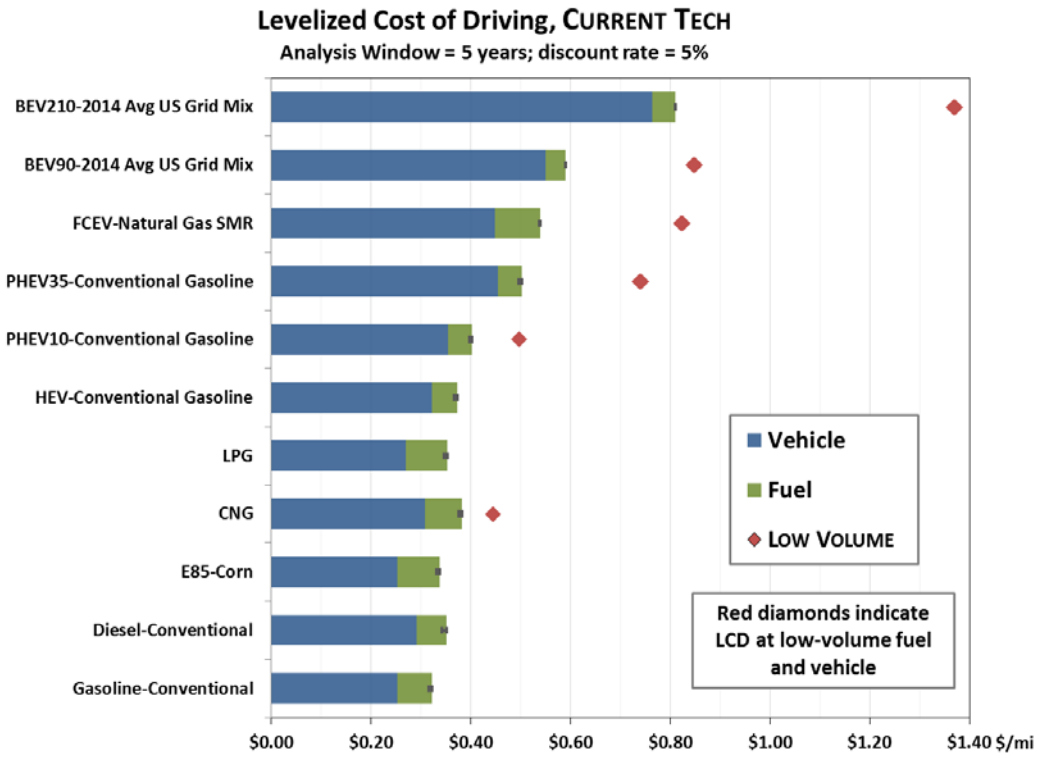

Figure 28. LCD results for the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases, 5-year analysis window, 5% discount rate base case

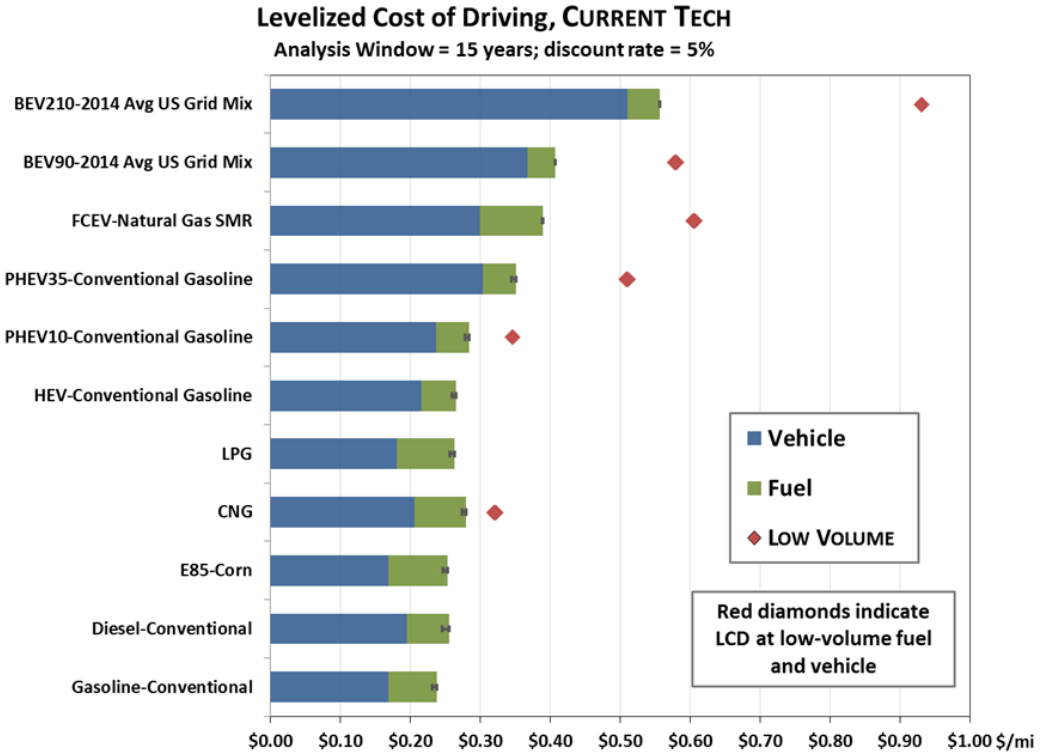

Figure 29. LCD results for the CURRENT TECHNOLOGY, HIGH VOLUME and CURRENT TECHNOLOGY, LOW VOLUME cases, 15-year analysis window, 5% discount rate case

9.4 Oil Price Sensitivity

We assumed a gasoline cost of $1.80 / gallon (Table 31) and gasoline SI ICEV fuel economy of 26.2 mpg for the Current Technology case. Historically, oil price has varied widely, as shown in Figure 30 (EIA 2016a). Consumer gasoline prices include taxes and retail markup but otherwise track crude oil prices quite well, as shown in Figure 31 (EIA 2016b). When this report was written (March 2016), oil prices, and hence gasoline costs, were lower than those projected in the AEO 2015 report. It is germane to consider the question of how a decrease in assumed gasoline costs affects the results of this study. To address this question, it is worth noting that a change of $1/gal in the gasoline cost translates into a change of $0.038/mi in fuel cost. This can be compared to the 3-year and 15-year LCDs of $0.36 and $0.24 (see Figure 24), which shows that the LCD is relatively insensitive to changes in fuel cost. As seen from inspection of Figure 24, the gasoline ICEV has the lowest LCD. Hence, decreases in the cost of gasoline (from the $1.80/gal value assumed) would not affect the rank order for technologies considered in this study. Appendix F examines the effect of an increase in the cost of gasoline, through analysis of the 2014 and 2015 versions of the EIA AEO.

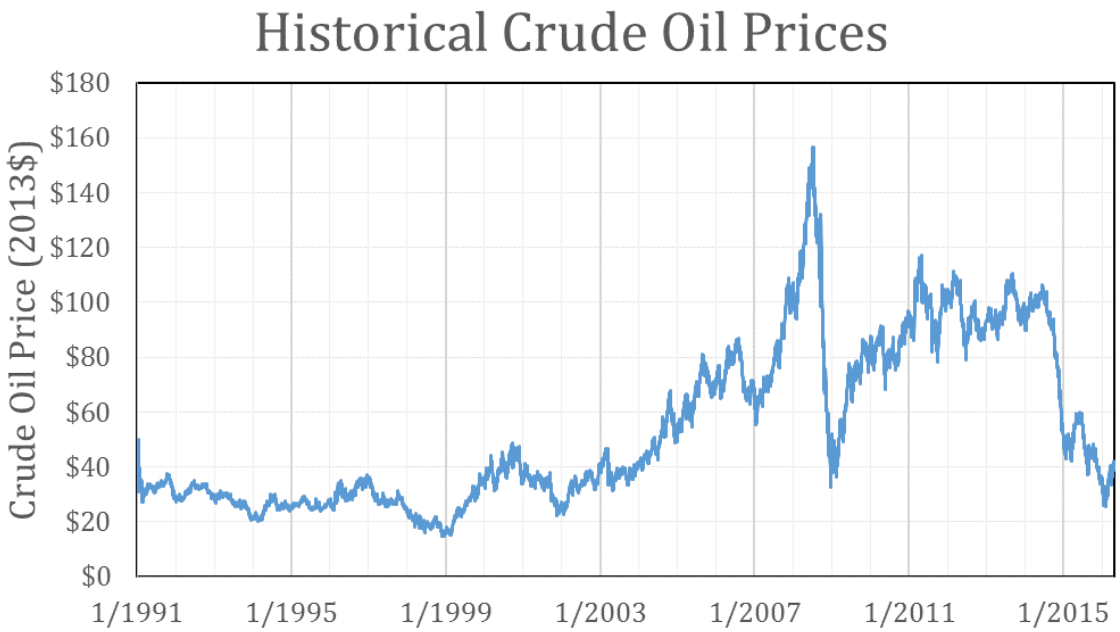

Figure 30. Historical crude oil spot prices for Cushing, OK, West Texas Intermediate, 1991–2016, daily averages (EIA 2016a)

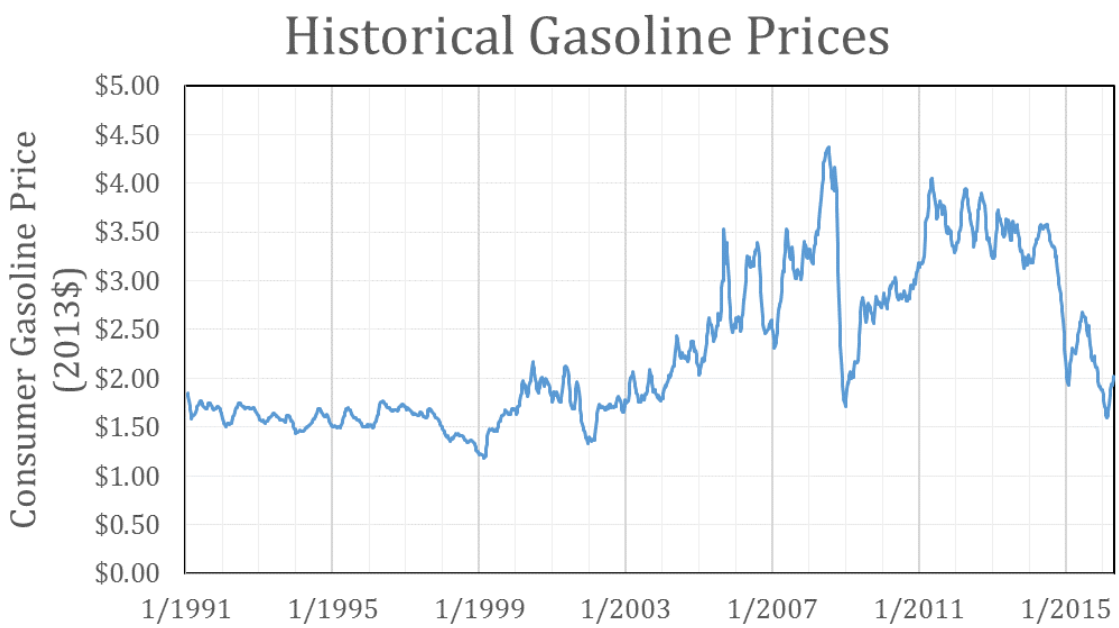

Figure 31. Historical consumer gasoline prices, including taxes and retail markup, 1991–2016, weekly averages (EIA 2016b)

9.5 References for Section 9

EIA (U.S. Energy Information Administration), 2016a. Pe*troleum and Other Liquids; Cushing, OK WTI Spot Price FOB*. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RWTC&f=D

EIA, 2016b. *Petroleum and Other Liquids; Gasoline and Diesel Fuel Update*. http://www.eia.gov/petroleum/gasdiesel/

Francfort, J., B. Bennett, R. Carlson, T. Garretson, L.L. Gourley, D. Karner, M. Kirkpatrick, P. McGuire, D. Scoffield, M. Shirk, S. Salisbury, S. Schey, J. Smart, S. White, and J. Wishart, 2015. *Plug-in Electric Vehicle and Infrastructure Analysis*. Report INL/EXT-15-35708, Idaho National Laboratory. http://avt.inel.gov/summaryreport.shtml

NHTSA (National Highway Traffic Safety Administration), *National Center for Statistics and Analysis, 2006. Vehicle Survivability and Travel Mileage Schedules*. http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf

10 COST OF AVOIDED GHG EMISSIONS

To allow comparison across different strategies for GHG mitigation, it is important to evaluate the cost-effectiveness of potential reductions in GHG emissions for each of the various vehicle-fuel combinations addressed in this study. This section outlines the methodology used to estimate a "cost of avoided GHG emissions" metric, which is based on a comparison of the alternative vehicle-fuel pathway to an equivalent gasoline ICEV. The costs of avoided GHG emissions for each vehicle-fuel pathway are reported in dollars per tonne (1,000 kg) of avoided GHG emissions, measured on a CO_2e basis.

The interpretation of GHG abatement costs embodied in this metric has limitations. The vehicle technologies considered in this analysis differ not only in their lifetime GHG emissions but also in other important attributes, such as local air quality-related emissions, reliance on different fuels (e.g., petroleum, NG, ethanol, hydrogen, electricity), and functionality (e.g., more limited range and longer refueling times for BEVs). The cost of avoided GHG emissions metric, by the definition used in this study, implicitly assumes that all vehicle and fuel changes (and their resulting costs) are undertaken to reduce GHG emissions. Consequently, this approach assumes that differences other than GHG emissions between the vehicles have zero value or cost. While this is clearly an oversimplification, and factors other than GHG emissions need to be considered, this approach is valuable in providing a starting point for discussions of the cost-effectiveness of different potential vehicle-fuel actions in terms of GHG abatement. The cost of avoided GHG emissions in this report are a direct measure of additional costs associated with reducing emissions in transportation, and thus not commensurate with broader aspects, for example, a social cost of carbon, defined as an estimate of the monetized damages associated with a marginal increase in carbon emissions, such as changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change (White House 2013b).

10.1 ANALYSIS FRAMEWORK

In this analysis, the cost of carbon avoided represents the cost of displaced carbon by driving a mile with an alternative vehicle compared to a mile driven by the baseline conventional gasoline ICEV. The cost of avoided GHG emissions analysis relies on the results of lifecycle GHG emissions assessment (Section 8) and the LCD analysis (Section 9). The cost of avoided GHG emissions (in \$/tonne CO_2e) metric is calculated from the difference in the cost of driving an alternative vehicle-fuel platform compared to a gasoline ICEV divided by the difference in the GHG emissions of the alternative vehicle compared to a gasoline ICEV (see Figure 32). The analysis is conducted for both the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases, with the alternative vehicle platform compared to the equivalent CURRENT TECHNOLOGY, HIGH VOLUME (2015) and FUTURE TECHNOLOGY, HIGH VOLUME (2025–2030) ICEVs, respectively. The calculation was conducted considering full lifetime (15-year) costs and emissions.[16] The 15-year analysis represents the full lifetime of the vehicle and thus provides a measure of the full societal cost of reducing GHG emissions. A sensitivity case was also developed using a 3-year ownership period, with the 3-year analysis timeframe designed to estimate the cost of avoided emissions from a first-owner standpoint.

[16] As an example, in the CURRENT TECHNOLOGY, HIGH VOLUME case (Table 54), the gasoline HEV pathway has a 15-year LCD of \$0.265/mi, compared to the 15-year LCD of \$0.238/mi for gasoline ICEVs (values are rounded as shown in Table 54). GHG emissions of HEVs are 343 g CO_2e/mi, compared to 457 g CO_2e/mi for ICEVs. The cost of avoided carbon for the HEV pathway is (\$0.27-\$0.24) ÷ ((457 – 343)/1,000,000). When solved using actual (non-rounded) values, this equates to a cost of avoided carbon of \$241/tonne. This is reported in a rounded format as \$240/tonne in Table 56.

$$\text{Cost of Avoided GHG Emissions } (\$/\text{tonne } CO_2e) = \frac{\text{Levelized Cost of Driving for Alternative Vehicle } (\$/\text{mi driven}) - \text{Levelized Cost of Driving for Gasoline ICE } (\$/\text{mi driven})}{\text{C2G GHG Emissions for Gasoline ICE } (\text{tonne } CO_2e/\text{mi driven}) - \text{C2G GHG Emissions for Alternative Vehicle } (\text{tonne } CO_2e/\text{mi driven})}$$

Figure 32. Cost of avoided GHG emissions calculation

By relying on the difference in emissions on a per-mile basis, the cost of avoided GHG emission metric captures the costs borne on a per-vehicle standpoint (or alternatively on a full vehicle fleet basis). Consistent with the framework for fuels studied in this report, the cost of avoided GHG emissions thus considers the alternative vehicle-fuel platforms on a pathway basis. The cost of avoided GHG emissions analysis is not a scenario analysis in that it does not project economy-wide total GHG reductions based on predicted vehicle-fuel penetration rates into the light-duty vehicle market or vehicle usage.[17]

The alternative vehicle-fuel platforms in the FUTURE TECHNOLOGY, HIGH VOLUME case are compared to an improved (model year 2025–2030) gasoline ICEV, and therefore the cost of avoided GHG emissions metric only considers the cost of GHG reductions specifically associated with the alternative vehicle-fuel technologies. This study does not address the cost of avoided GHG emissions for improvements to the vehicle glider (e.g., reduced weight, reduced rolling resistance, improved aerodynamics, etc.) that are common to both the gasoline ICEV baseline and the alternative vehicle-fuel platforms.

10.2 COST OF AVOIDED GHG EMISSIONS: CURRENT TECHNOLOGY CASE

The CURRENT TECHNOLOGY, HIGH VOLUME case considers the cost of avoided GHG emissions based on MY2015 vehicle technologies with vehicle costs modeled at high-volume production at a level at or above optimal scale. Fuel costs are also modeled for 2015, with fuels assumed to be produced at scale (i.e., a high-volume fuel cost is used in the analysis). All costs are presented in 2013$. Key data for the cost of avoided GHG emissions are shown in Table 54 and include vehicle cost, fuel cost, vehicle fuel economy, vehicle-fuel pathway GHG emissions, and the 3-year and 15-year LCDs (see Sections 5, 6, 8, and 9).

As noted in Section 9, the LCD accounting includes the vehicle cost (less its residual value in the 3-year case) and the fuel cost, but it does not include other costs of driving, such as maintenance and repairs, insurance, registration and taxes, etc. Sufficient data to differentiate these costs across vehicle-fuel platforms were not available. In the absence of data to the contrary, we assumed that costs associated with maintenance and repairs, insurance, registration, and taxes were equal across platforms and hence do not factor into the estimation of CO_2 abatement cost.

[17] As discussed in Section 9, the BEV90 is assumed to drive only 70% of the lifetime miles as the other vehicles considered in this study due to its reduced range.

Table 54. Key data used in the cost of avoided GHG emissions metric for the CURRENT TECHNOLOGY, HIGH VOLUME case

Base Case (5% discount rate, mid-point vehicle and fuel cost)		**Vehicle Cost (2013$)**	**Fuel Cost ($/gge)**	**Vehicle F/E (mpgge)**	**GHG Emissions (g CO_2e/mi)**	**3-year Cost ($/mi)**	**15-year Cost ($/mi)**
Fuel	**Pathway**						
Gasoline ICEV	Conventional gasoline	21,384	1.80	26.2	457	0.36	0.24
Diesel	Conventional diesel	24,697	1.90	31.6	387	0.39	0.26
E85	Corn	21,384	2.21	26.2	366	0.37	0.25
CNG	CNG	26,121	2.04	27.6	373	0.43	0.28
LPG	LPG	22,881	2.17	26.2	410	0.39	0.26
HEV	Conventional gasoline	27,327	1.80	36.5	343	0.42	0.27
PHEV10	Conventional gasoline	30,029	1.96	41.4	337	0.45	0.28
PHEV35	Conventional gasoline	38,442	2.54	53.7	325	0.57	0.35
FCEV	H_2 from NG reformation	37,923	4.90	54.1	316	0.60	0.39
BEV90	U.S. grid mix (2014 avg.) electricity	32,598	3.98	100.5	301	0.67	0.41
BEV210	U.S. grid mix (2014 avg.) electricity	64,598	3.98	84.6	336	0.92	0.56

The cost of avoided GHG emissions results for the CURRENT TECHNOLOGY, HIGH VOLUME case are shown in Figure 33. The darker bars of Figure 33 represent the cost of avoided GHG emissions metric computed for the full 15-year vehicle lifetime. The costs of avoided GHG emissions for most vehicle-fuel pathways fall within the range of $100/tonne CO_2e to $1,000/tonne CO_2e. One exception is the BEV210. The high cost of a long-range battery pack using today's technology (see Section 6) results in a high vehicle cost for the BEV210. This in turn results in a higher cost of avoided GHG emissions for this platform at $2,600/tonne CO_2e.

The lighter bars in Figure 33 represent the sensitivity for a 3-year ownership period. These show that from the perspective of a first owner, the costs of avoided GHG emissions are higher than those for the full vehicle lifetime, reflecting that over a shorter use period, the metric is more sensitive to vehicle cost differences. The 3-year costs of avoided GHG emissions range from $100s to $1,000s per tonne CO_2e, with most of the vehicle-fuel platforms avoiding GHG emissions for less than $2,000/tonne CO_2e. The BEV210 platform has a cost of avoided GHG emissions for the first owner at $4,700/tonne CO_2e.

10.3 COST OF AVOIDED GHG EMISSIONS: FUTURE TECHNOLOGY CASE

The FUTURE TECHNOLOGY, HIGH VOLUME case considers the modeled cost of avoided GHG emissions based on MY2025–2030 vehicle technologies. As with the CURRENT TECHNOLOGY, HIGH VOLUME case, vehicle costs are modeled at high-volume production. Fuel costs are also modeled for 2025–2030, with fuels assumed to be produced at scale. Again, costs are presented in 2013$. Key data for the cost of avoided GHG emissions are shown in Table 55 and include vehicle cost, fuel cost, vehicle fuel economy, vehicle-fuel pathway GHG emissions, and the 3-year and 15-year LCDs (see Sections 5, 6, 8, and 9). Similar to the CURRENT TECHNOLOGY, HIGH VOLUME case, the LCD accounting includes the vehicle cost (less its residual value in the 3-year case) and the fuel cost, but it does not include other costs of driving, such as insurance, vehicle registration, and vehicle repair and maintenance.

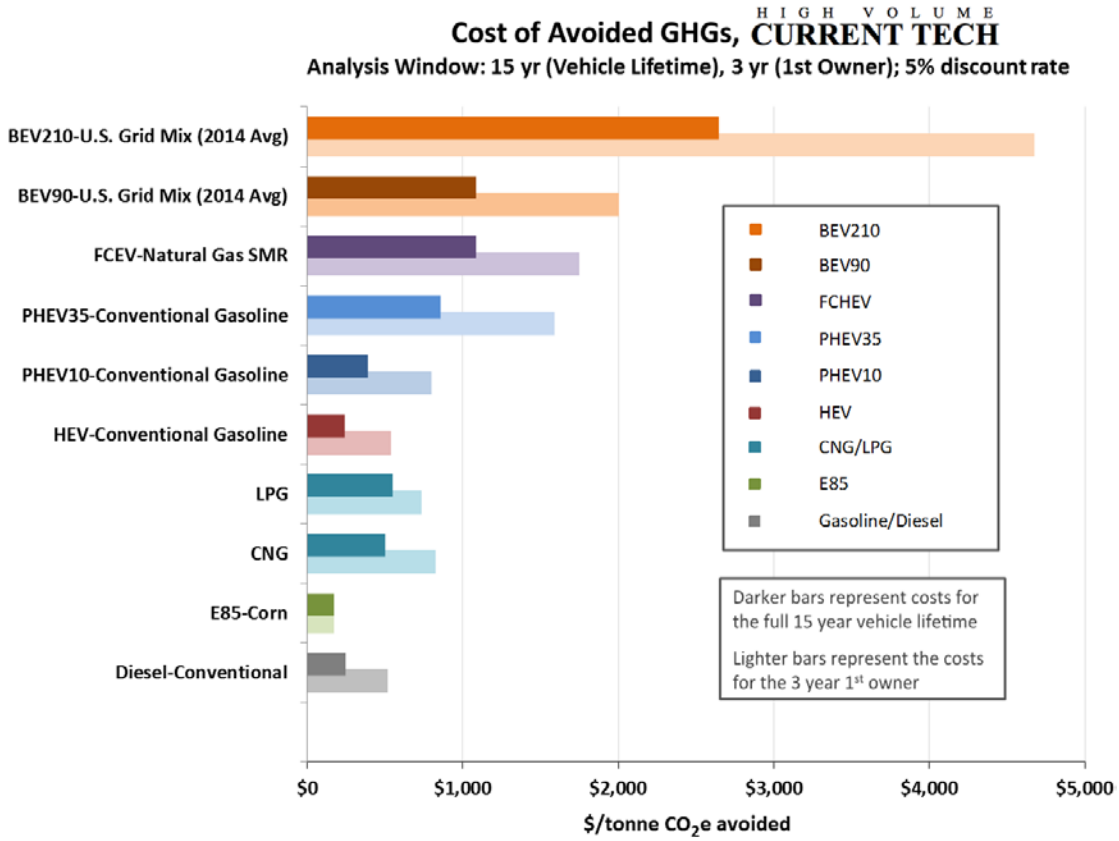

Figure 33. Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case, relative to the CURRENT TECHNOLOGY gasoline ICEV

The modeled cost of avoided GHG emissions analysis results for the FUTURE TECHNOLOGY, HIGH VOLUME case is shown in Figure 34. Modeled costs of avoided GHG emissions for the FUTURE TECHNOLOGY, HIGH VOLUME case, considering the full 15-year vehicle lifetime (darker bars in Figure 34), are below \$400/tonne CO_2e, with the exception of the compression-ignition (i.e., diesel) fuel pathways, the BEV90 ACC pathway, and the BEV210. The BEV210 pathway in particular is markedly different from the CURRENT TECHNOLOGY, HIGH VOLUME case. The cost of the BEV210 battery pack, though still a major component of overall vehicle cost, is modeled to improve significantly over the intervening time, leading to a much lower total vehicle cost. As a result, the cost of avoided GHG emissions from the BEV210 pathway falls from over \$2,400/tonne CO_2e in the CURRENT TECHNOLOGY, HIGH VOLUME case to about \$400/tonne in the FUTURE TECHNOLOGY, HIGH VOLUME case.

For the FUTURE TECHNOLOGY, HIGH VOLUME case, HEV and PHEV platforms offer the lowest modeled costs of avoided GHG emissions, with costs below \$170/tonne CO_2e. Two of the diesel fuel pathways project relatively high costs for avoided GHG emissions. Over a 15-year lifetime, the cost of avoided GHG emissions modeling finds that conventional diesel reduces GHG emissions at a cost of \$570/tonne CO_2e and FTD reduces GHG emissions at a cost of \$1,100/tonne CO_2e. The large increase in the cost of avoided GHG emissions for conventional diesel from the CURRENT TECHNOLOGY, HIGH VOLUME to the FUTURE TECHNOLOGY, HIGH VOLUME case reflects the compounding effect of two factors. First, gasoline vehicles become more diesel-like in their efficiency (the CO_2 benefit drops from 70 g CO_2e/mi to 29 g CO_2e/mi). Second, the cost of diesel fuel increases relative to gasoline (from \$0.05 less expensive to \$0.10 more expensive per gge).

Table 55. Key data used in the cost of avoided GHG emissions metric for the FUTURE TECHNOLOGY, HIGH VOLUME case

Base Case (5% discount rate, mid-point vehicle and fuel cost)		**Vehicle Cost (2013$)**	**Fuel Cost ($/gge)**	**Vehicle F/E (mpgge)**	**GHG Emissions (g CO_2e/mi)**	**3-year Cost ($/mi)**	**15-year Cost ($/mi)**
Vehicle	**Fuel**						
Gasoline ICEV	Conventional gasoline	23,491	2.44	34.5	352	0.39	0.26
Gasoline ICEV	Pyrolysis gasoline	23,491	4.17	34.5	142	0.44	0.31
Diesel	Conventional diesel	25,839	2.60	38.1	323	0.42	0.27
Diesel	Pyrolysis diesel	25,839	4.17	38.1	128	0.46	0.31
Diesel	FAME (B20)	25,839	2.72	38.1	305	0.42	0.28
Diesel	HRD (B100)	25,839	4.24	38.1	203	0.46	0.32
Diesel	GTL FTD	25,839	4.14	38.1	313	0.46	0.31
E85	Corn stover ethanol	23,491	4.60	36.2	145	0.45	0.31
HEV	Pyrolysis gasoline	25,561	4.17	53.5	107	0.42	0.28
PHEV10	Pyrolysis + wind electricity	26,150	4.20	57.7	98	0.43	0.28
PHEV10	Pyrolysis + ACC w/CCS	26,150	4.27	57.7	104	0.43	0.28
PHEV35	Pyrolysis + wind electricity	29,885	4.31	72.0	73	0.46	0.30
PHEV35	Pyrolysis + ACC w/CCS	29,885	4.62	72.0	94	0.47	0.30
FCEV	H_2 via wind electrolysis	30,264	7.41	72.0	53	0.51	0.34
FCEV	H_2 via NG SMR w/CCS	30,264	4.59	72.0	132	0.47	0.30
FCEV	H_2 via woody biomass gasification	30,264	4.78	72.0	114	0.48	0.31
BEV90	Electricity via ACC (no CCS)	27,057	4.23	119.5	185	0.56	0.34
BEV90	Electricity via ACC w/CCS	27,057	5.43	119.5	88	0.57	0.35
BEV90	Wind electricity	27,057	4.56	119.5	52	0.56	0.34
BEV90	Electricity via solar PV	27,057	5.90	119.5	52	0.57	0.35
BEV210	Electricity via ACC (no CCS)	43,056	4.23	119.5	191	0.62	0.38
BEV210	Electricity via ACC w/CCS	43,056	5.43	105.1	81	0.63	0.39
BEV210	Wind electricity	43,056	4.56	105.1	41	0.63	0.38
BEV210	Electricity via solar PV	43,056	5.90	105.1	41	0.64	0.40

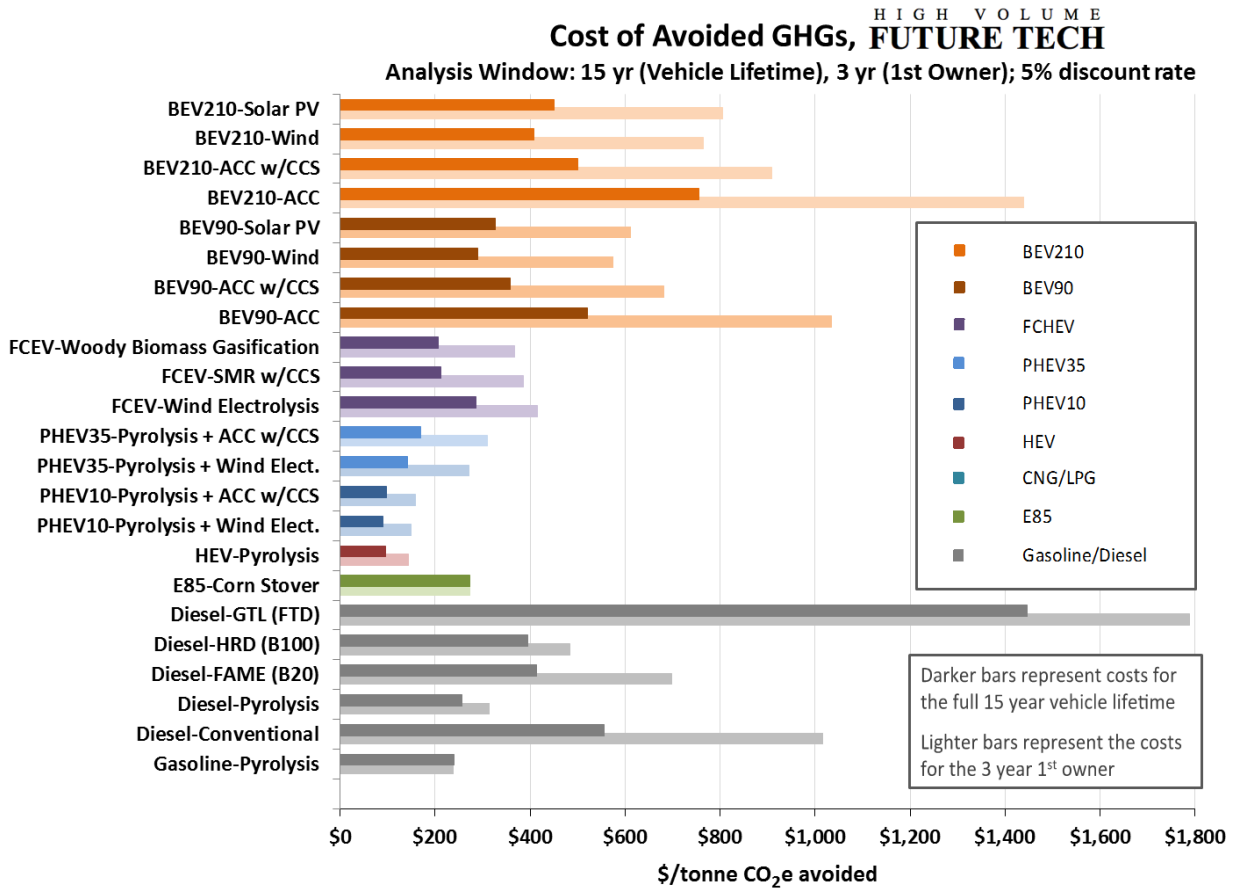

Figure 34. Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case, relative to the FUTURE TECHNOLOGY gasoline ICEV

As in the CURRENT TECHNOLOGY, HIGH VOLUME case, the sensitivity case of 3-year ownership (shown as the lighter bars in Figure 34) shows modeled costs that are higher than those for the 15-year full vehicle lifetime calculation. The 3-year ownership costs of avoided GHG emissions range from $100 to $1,500/tonne CO_2e in the FUTURE TECHNOLOGY, HIGH VOLUME case.

Table 56 summarizes the cost of avoided GHG emissions results for all CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME vehicle-fuel pathways.

Again, note the limitations of the GHG abatement cost metric "$/tonne CO_2e avoided" shown in Figure 33 and Table 56. The vehicle technologies considered in this analysis differ not only in their lifetime GHG emissions but also in other important attributes, such as local air quality-related emissions, reliance on different fuels (e.g., gasoline, NG, ethanol, hydrogen, electricity), functionality (e.g., more limited range and longer refueling times for BEVs, larger fuel tanks and vehicle packaging/range challenges for NG and fuel cell vehicles), and scalability (total abatement opportunity). Factors other than cost of avoided GHG emissions, such as air quality, reliance on different fuels, vehicle functionality (range, refueling time, packaging), and scalability (other than being able to meet at least approximately 10% of demand), are important but are not fully incorporated into this study.

Table 56. Cost of avoided GHG emissions results by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases, relative to their respective gasoline ICEVs

Cost of Avoided GHG Emissions Summary, Base Case (5% discount rate, mid-point vehicle and fuel cost)	**15 yr (Vehicle Lifetime)**		**3 yr (1st Owner)**	
Vehicle-Fuel Pathway	**Total GHGs Avoided per Vehicle** (tonnes CO_2e)	**Cost** ($/tonne CO_2e)	**Total GHGs Avoided per Vehicle** (tonnes CO_2e)	**Cost** ($/tonne CO_2e)
CURRENT TECHNOLOGY, HIGH VOLUME Case				
Diesel – conventional diesel	12.4	250	2.9	520
E85 – corn	16.1	170	3.8	170
CNG – CNG	14.9	500	3.5	820
LPG – LPG	8.3	550	1.9	730
HEV – conventional gasoline	20.3	240	4.8	530
PHEV10 – conventional gasoline	21.3	390	5.0	800
PHEV35 – conventional gasoline	23.5	860	5.5	1,600
FCEV – H_2 from NG reformation	25.0	1,080	5.9	1,700
BEV90 – U.S. grid mix (2014 avg.) electricity	19.4	1,090	4.6	2,000
BEV210 – U.S. grid mix (2014 avg.) electricity	21.5	2,600	5.0	4,700
FUTURE TECHNOLOGY, HIGH VOLUME Case				
Gasoline ICEV – pyrolysis gasoline	37.3	240	8.8	240
Diesel – conventional diesel	5.1	560	1.2	1,000
Diesel – pyrolysis diesel	39.8	260	9.3	320
Diesel – FAME (B20)	8.3	410	1.9	700
Diesel – HRD (B100)	26.6	400	6.2	480
Diesel – GTL FTD	6.9	1,400	1.6	1,790
E85 – corn stover ethanol	36.7	270	8.6	270
HEV – pyrolysis gasoline	43.6	100	10.2	140
PHEV10 – pyrolysis + wind electricity	45.3	90	10.6	150
PHEV10 – pyrolysis + ACC w/CCS	44.2	100	10.4	160
PHEV35 – pyrolysis + wind electricity	49.6	140	11.7	270
PHEV35 – pyrolysis + ACC w/CCS	46.0	170	10.8	310
FCEV – H_2 via wind electrolysis	53.2	290	12.5	410
FCEV – H_2 via NG SMR w/CCS	39.1	210	9.2	390
FCEV – H_2 via woody biomass gasification	42.4	210	10.0	370
BEV90 – electricity via ACC (no CCS)	20.8	520	4.9	1,030
BEV90 – electricity via ACC w/CCS	32.9	360	7.7	680
BEV90 – wind electricity	37.4	290	8.8	580
BEV90 – electricity via solar PV	37.4	330	8.8	610
BEV210 – electricity via ACC (no CCS)	28.7	750	6.7	1,440
BEV210 – electricity via ACC w/CCS	48.2	500	11.3	910
BEV210 – wind electricity	55.4	410	13.0	760
BEV210 – electricity via solar PV	55.4	450	13.0	810

10.4 SENSITIVITY ANALYSIS CASES

The base case modeling used for the LCD analysis (Section 9) and the cost of avoided GHG metric (this section) is based on reference (base case) vehicle and fuel costs. The base case modeling also assumes a discount rate of 5%. The FUTURE TECHNOLOGY, HIGH VOLUME case vehicle cost modeling includes low and high vehicle costs for each platform. Similarly, for the FUTURE TECHNOLOGY, HIGH VOLUME case, many of the fuels include low and high fuel costs (e.g., E85 from corn stover and fuels based on AEO 2015 projections). Additionally, for both the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases, the cost analysis includes sensitivity analyses around a 3% discount rate and 7% discount rate, in addition to the base case 5% discount rate.

The results in Sections 10.2 and 10.3 include analyses covering a 3-year and 15-year time horizon but do not include any sensitivity analysis results incorporating the range of vehicle and fuel costs or the range of discount rates. Section 9 includes the LCD results for sensitivity analyses incorporating both vehicle-fuel costs and discount rate.

To show the potential range in the cost of avoided GHG emissions metric for these various cost sensitivities, an analysis on the upper- and lower-bound costs of avoided GHG emissions was conducted for each vehicle-fuel platform. The boundaries for this analysis were: (1) baseline vehicle and fuel costs, using a discount rate of 3% and an analysis window of 15 years, and (2) baseline vehicle and fuel costs, using a discount rate of 7% and an analysis window of 3 years. As with the base case analysis, the cost of avoided GHG emissions metric for these boundary cases compares the alternative vehicle-fuel platform to a comparable gasoline ICEV. An uncertainty range was then developed for the upper- and lower-bound estimates using the high and low vehicle and fuel cost estimates for each pathway.

The results of these sensitivity analyses for the CURRENT TECHNOLOGY, HIGH VOLUME and FUTURE TECHNOLOGY, HIGH VOLUME cases are shown in Figures 35 and 36. Note that Figure 35 does not include the cost range for the BEV210 platform. For the CURRENT TECHNOLOGY, HIGH VOLUME case, the lower- to upper-bound cost range for avoided GHG emissions for the BEV210 platform is $2,000 to $5,000/tonne CO_2e. Note also that uncertainty bars are shown for all pathways, based on the effect of the range of high and low vehicle-fuel costs. For many pathways, especially in the CURRENT TECHNOLOGY, HIGH VOLUME case, the uncertainty bars cannot be seen in the figures, since the uncertainty range is very small (with marker diamonds covering the very small uncertainty range).

In addition to the sensitivity cases investigating the effects of discount rates, analysis period, and vehicle and fuel costs, a low-volume sensitivity analysis was conducted to investigate the effect that low-volume vehicle and fuel costs have on the cost of avoided carbon metric. This analysis is based on the results of the low-volume LCD evaluation (discussed in Section 9.3), which in turn was based on the low-volume vehicle costs (discussed in Section 6.5) for CNG ICEVs, PHEVs, FCEVs, and BEVs, as well as the low-volume cost of hydrogen fuel (discussed in Section 5). Using the LCD results for these early market vehicles together with the C2G GHG emissions for these vehicles discussed in Section 8, a low-volume assessment of the cost of avoided carbon was completed. The results of this low-volume sensitivity are shown in Figure 37 for the 5-year analysis window base case and in Figure 38 for the 15-year vehicle lifetime case.

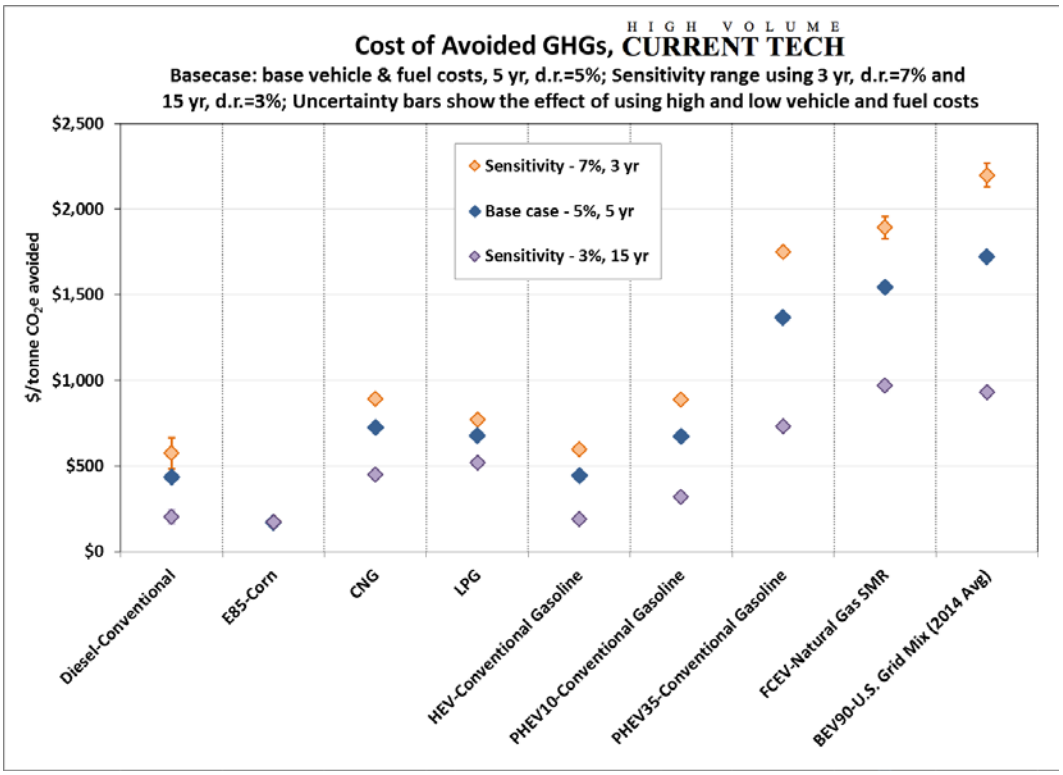

Figure 35. Range of CURRENT TECHNOLOGY case avoided GHG emissions results using 3 different analysis frameworks (see text)

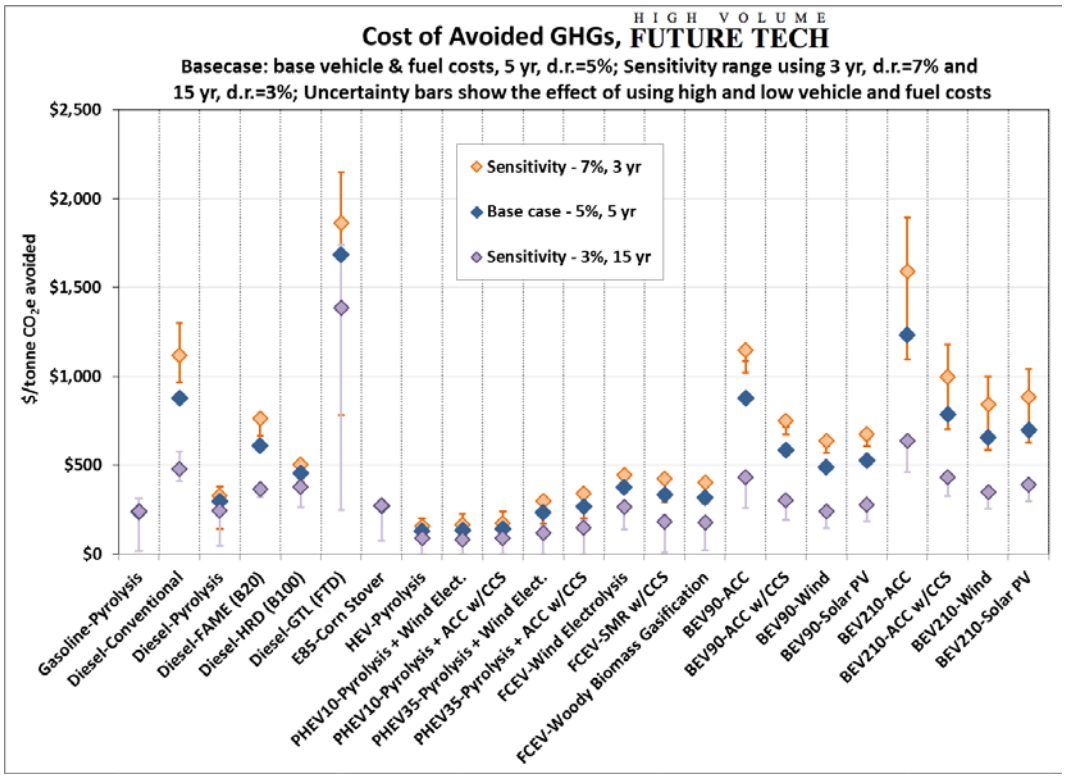

Figure 36. Range of FUTURE TECHNOLOGY case avoided GHG emissions results using 3 different analysis frameworks (see text)

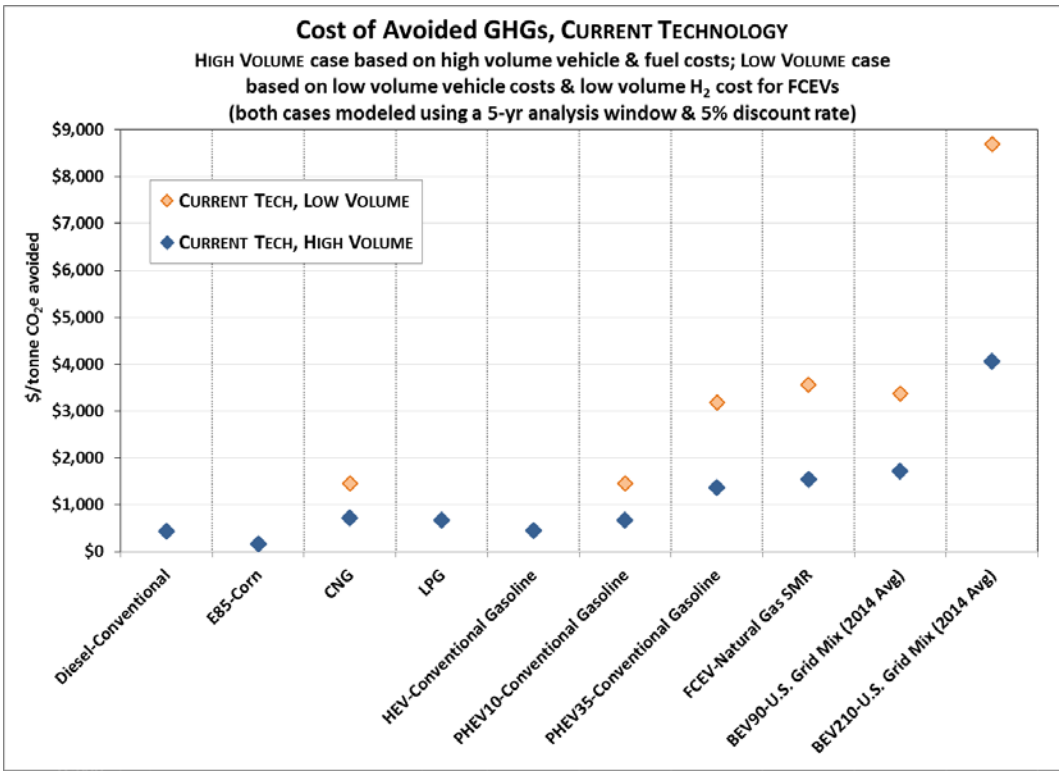

Figure 37. Cost of avoided GHG emissions for the Current Technology, High Volume and Current Technology, Low Volume cases, base case

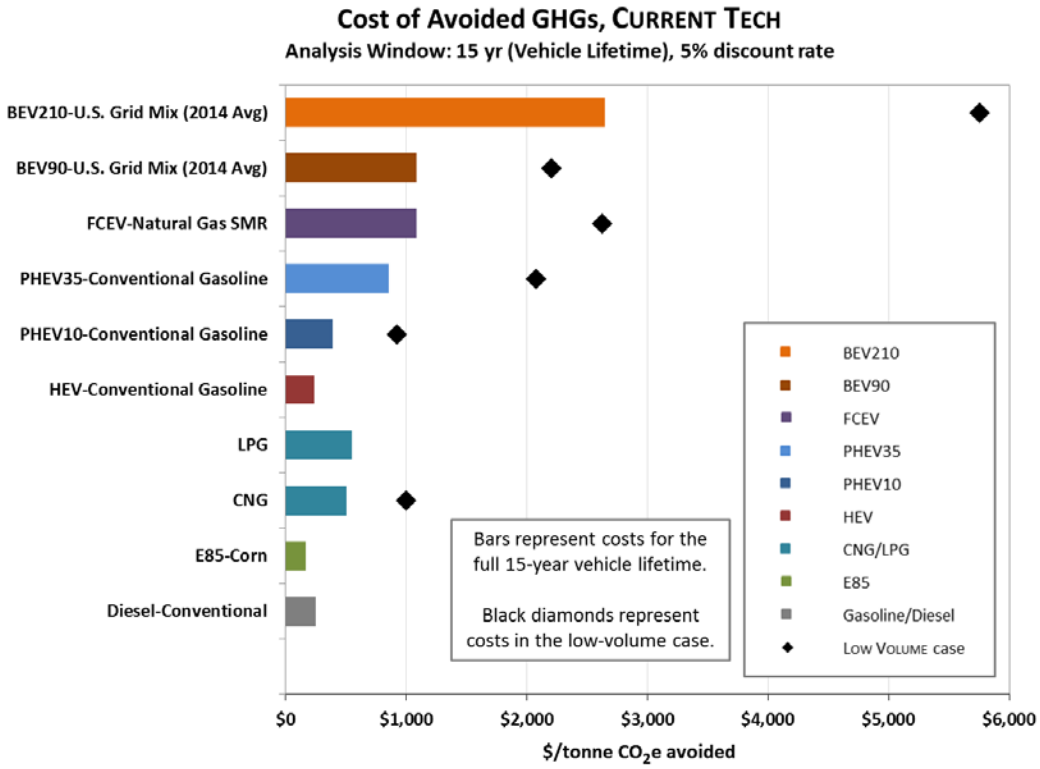

Figure 38. Cost of avoided GHG emissions for the Current Technology, High Volume and Current Technology, Low Volume cases, 15-year lifetime analysis window

The effect on the lifecycle GHG emissions associated with LUC for the corn ethanol (E85 CURRENT TECHNOLOGY, HIGH VOLUME case), FAME, and HRD pathways are discussed in Section 8.1. Since the cost of avoided GHG emissions depends on different assumptions made regarding LUC-associated GHG emissions, a sensitivity analysis was conducted to characterize the impact of varying LUC assumptions on the cost of avoided carbon metric for the E85 pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case and the FAME (B20) and HRD pathways for the FUTURE TECHNOLOGY, HIGH VOLUME case. Figure 39 shows the range of costs of avoided GHG emissions assuming no LUC and high LUC, as well as the base case results for these pathways.

For the E85 CURRENT TECHNOLOGY case, the no-LUC sensitivity has lifecycle emissions of 340 g CO_2e/mi. EPA (2010c) represents the high estimate of LUC that still yields GHG reductions (lifecycle emissions of 434 g CO_2e/mi). For E85, Searchinger et al. (2008) estimates larger LUC-related emissions, leading to lifecycle GHG emissions of 685 g CO_2e/mi. As this level of emissions exceeds the emissions of a conventional gasoline ICEV, no emissions reductions are associated with E85 use when this level of LUC-induced emissions are assumed, leading to an infinite cost of reduced avoided carbon emissions (shown as a dotted line in the figure). For the FAME (B20) and HRD (B100) FUTURE TECHNOLOGY pathways, LUC data from Section 8.1 do not show a significant variance from the LUC-related emissions that are captured in GREET. For these pathways, a sensitivity analysis was conducted to understand the effect if no LUC-related emissions are considered.

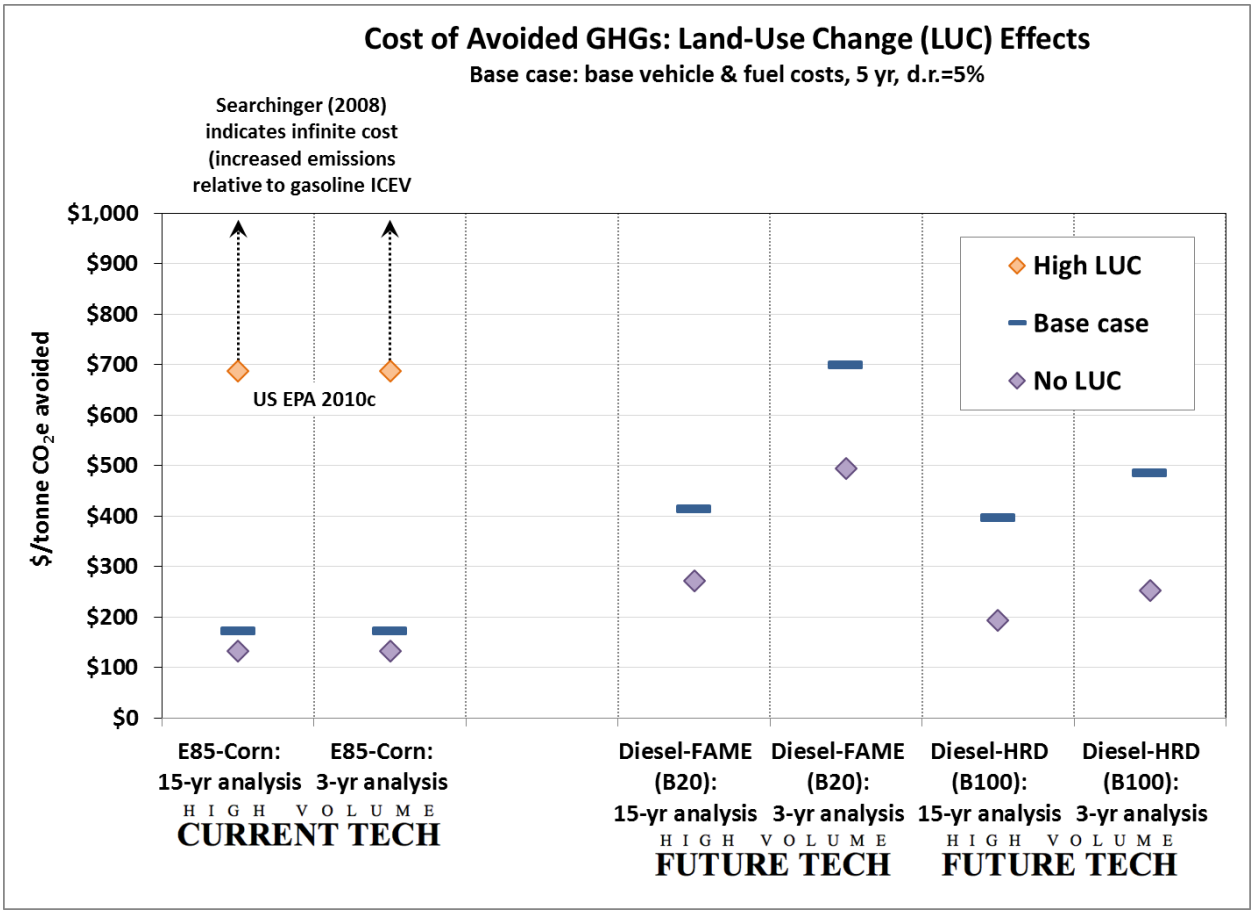

Figure 39. Effect of different LUC assumptions on the cost of avoided GHG emissions for the E85, FAME, and HRD pathways

10.5 REFERENCES FOR SECTION 10

ATLASS Consortium, 2011. *Assessing the Land Use Change Consequences of European Biofuel Policies*. http://trade.ec.europa.eu/doclib/html/148289.htm

CARB (California Air Resources Board), 2015. *Low Carbon Fuel Standard Regulation*. http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

Elliott, J., B. Sharma, N. Best, M. Glotter, J.B. Dunn, I. Foster, F. Miguez, S. Mueller, and M. Wang, 2014. "A Spatial Modeling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions." *Environ. Sci. Technol*., 2014, 48 (4), pp 2488–2496, DOI: 10.1021/es404546r. http://pubs.acs.org/doi/abs/10.1021/es404546r

EPA (U.S. Environmental Protection Agency), 2010c. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.* Report EPA-420-R-10-006. http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen, 2010. "Effects of US Maize Ethanol in Global Land Use and Greenhouse Gas Emissions: Estimating Market-Mediated responses." *Bioscience*, 60:223e31.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu, 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change," *Science*, 319(5867), pp. 1238–1240, DOI: 10.1126/science.1151861. http://science.sciencemag.org/content/319/5867/1238.abstract

Tyner, W.E., F. Taheripour, Q. Zhuang, D. Birur, and U. Baldos, 2010. *Land Use Changes and Consequent CO_2 Emissions Due to US Corn Ethanol Production: A Comprehensive Analysis*. Purdue University, Department of Agricultural Economics. https://www.gtap.agecon.purdue.edu/resources/download/5200.pdf

White House, Interagency Working Group on Social Cost of Carbon, 2013b. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf

11 LIMITATIONS AND FUTURE IMPLICATIONS

While climate change is of increasing global concern, and thus requires lifecycle analysis of GHG emissions, other metrics should be considered when evaluating the environmental impacts of various vehicle-fuel systems, such as air emissions and water use, where impacts are regional rather than global. For example, the California LCFS addresses GHG emissions, while its Zero-Emission Vehicle (ZEV) mandate addresses all atmospheric emissions.

To serve the analytic purpose of this study, we evaluated vehicle-fuel pathways on a common production volume basis. However, the current and future production volumes for various fuels and vehicles will vary greatly. Market potential and economic impacts of various vehicle-fuel technologies should be considered from a more realistic perspective with respect to production volumes in the future. This study attempted to address the market readiness of various vehicle-fuel systems by qualitatively assigning TRLs to key elements impacting marketability of various vehicle-fuel systems to inform of the challenges associated with the deployment of each technology that should be considered when understanding the results of this study. However, certain technologies are more uncertain than others (e.g., CCS) because they are at a lower TRL compared to others. Other challenges, such as infrastructure availability for certain fuels (e.g., hydrogen, electricity for vehicle charging, and ethanol) requires more careful analysis. Marketability of final fuel and vehicle strongly depends on their costs, which this study attempted to evaluate quantitatively. However, other factors that impact consumer choice are not covered in this study. Furthermore, the cost estimates in this study are subject to uncertainties due to their projection at both high-volume and low-volume production for the CURRENT TECHNOLOGY case and their dependence also on technology advancement for the FUTURE TECHNOLOGY case.

Key parameters influencing the results of various pathways are subject to different degrees of uncertainty. For example, methane emissions of the CURRENT TECHNOLOGY NG pathway vary greatly between the various studies. Land use change induced by large-volume biofuel production is another example of uncertainty and varies greatly between studies. Some fuel pathways were examined in detail in this study, while information on other fuel pathways was extracted from other studies (e.g., for FTD, HRD, pyrolysis, and LUC), and thus may not have the same common assumptions (e.g., rate of return on investment, plant life, etc.) that drive the cost estimates as the pathways that were examined in detail.

AEO 2015 data for prices of crude oil, gasoline, and diesel fuel used in the CURRENT TECHNOLOGY case differ from subject data reported in early 2016. It should be noted that because these data are different and because they are among several factors considered in this analysis, the calculated CURRENT TECHNOLOGY LCDs for gasoline and diesel and the CURRENT TECHNOLOGY cost of avoided GHGs for the other alternative pathways relative to gasoline would be different if 2016 prices were used. This is examined in greater detail in Section 9.4 and Appendix F.

Finally, this study evaluated GHG emissions and cost of individual pathways and assumed common vehicle platforms for comparison. However, market scenario analysis should be incorporated into this pathway analysis to explore the realistic potential of the mix of different pathways to achieve GHG emissions targets in different regions. The cost of avoided carbon emissions is an informative metric that improves the comparison of various technologies. However, other co-benefits vary between the various pathways, such as criteria air pollutants and water use.

12 CONCLUSIONS

We report the results of a comprehensive study of the C2G costs, energy consumption, GHG emissions, and carbon abatement costs (relative to conventional gasoline ICEVs) for representative vehicle-fuel technologies under consideration for future deployment in the United States. Conclusions related to emissions, costs, costs of carbon abatement, and technology feasibility in this report are summarized below.

Emissions

- Large GHG reductions for LDVs are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

Costs

- High-volume production is critical to the viability of advanced technologies.
- Incremental costs of advanced technologies in FUTURE TECHNOLOGY, HIGH VOLUME cases are significantly reduced, reflecting estimated R&D outcomes.
- Low-carbon fuels can have significantly higher costs than conventional fuels.
- Vehicle cost is the major (60–90%) and fuel cost the minor (10–40%) component of LCD when projected at volume. Treatment of residual vehicle cost is an important consideration. Many alternative vehicles and/or fuels cost significantly more than conventional gasoline vehicles for the CURRENT TECHNOLOGY case, even when costs are projected for high-volume production.

Costs of Carbon Abatement

- For the CURRENT TECHNOLOGY, HIGH VOLUME case, carbon abatement costs are generally on the order of \$100s per tonne CO_2 to \$1,000s per tonne CO_2 for alternative vehicle-fuel pathways compared to a conventional gasoline vehicle baseline.
- FUTURE TECHNOLOGY, HIGH VOLUME carbon abatement costs are generally expected to be in the range \$100–\$1,000/tonne CO_2.

Technology Feasibility

- Significant technical barriers still exist for the introduction of some alternative fuels. Further, market transition barriers – such as low-volume costs, fuel or make/model availability, and vehicle/fuel/infrastructure compatibility – may play a role as well.

Appendix A: Description of Fuel Production Pathways: Key Stages and Parameters

This appendix summarizes the key parameters of the fuel production pathways analyzed to determine lifecycle emissions and energy usage. The GREET 2014 estimates for several key parameters that impact GHG emission results are included here. These pathways are discussed in greater detail in Section 4.

A.1 Petroleum Pathways: Gasoline, Diesel, and LPG

Figure A.1 illustrates basic production steps for petroleum fuels.

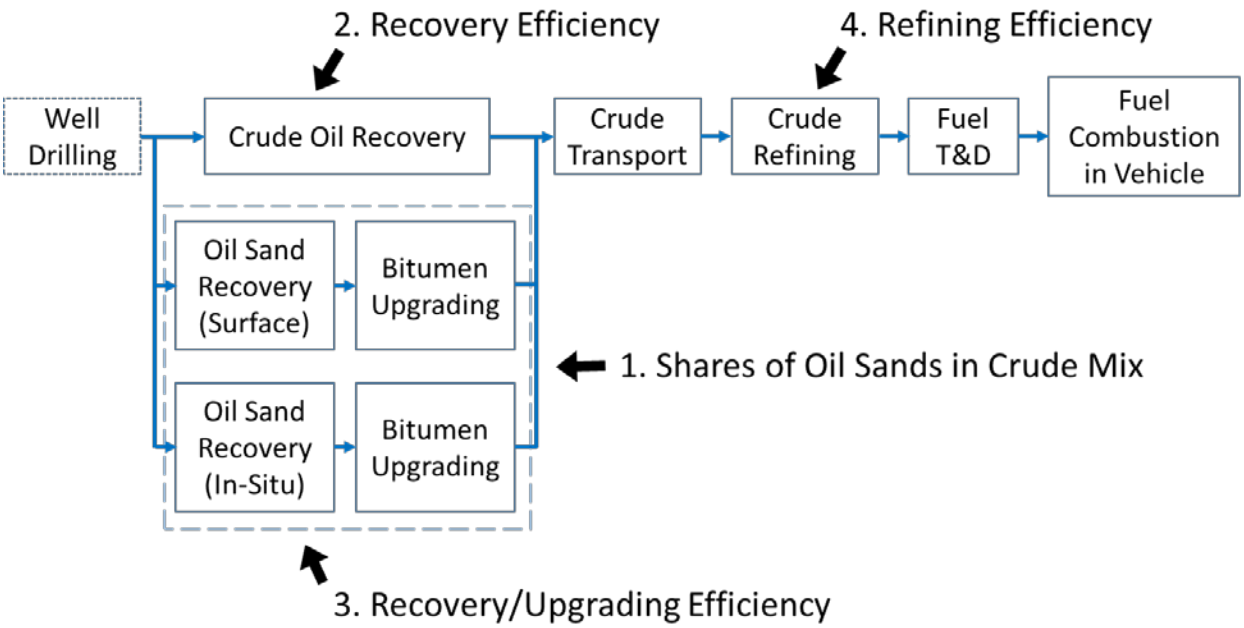

Figure A.1. Petroleum gasoline, diesel, and LPG fuel cycle

To evaluate the entire lifecycle of petroleum pathways, we consider well drilling, oil recovery, transport, refining, distribution, and combustion. In particular, conventional crude oil recovery includes:

- Average energy efficiency for conventional crude recovery and
- CO_2 emissions from flaring and methane emissions from venting of associated gas (via combustion and fugitive emissions).

Oil sands recovery and upgrading addresses the:

- Share of oil sand-derived crudes in crude oil supply to U.S. refineries;
- Average energy efficiency for oil sands recovery via surface mining with and without upgrading;
- Average energy efficiency for oil sands recovery via *in situ* production with and without upgrading; and
- Shares of oil sands crude recovered via surface mining and *in situ* production, with and without upgrading.

The analysis of refining includes refinery process fuel use for the production of gasoline, diesel, and LPG.

The GREET 2014 estimates for the above parameters are provided in the following tables:

Share of crude supply to U.S. refineries							
Case	**U.S.**	**Canada**	**Mexico**	**Middle East**	**Latin America**	**Africa**	**Others**
CURRENT TECHNOLOGY	49.1%	17.0%	5.6%	13.2%	9.9%	4.2%	1.0%
FUTURE TECHNOLOGY	46.7%	22.4%	6.5%	5.7%	8.4%	8.1%	2.2%

Energy efficiency of extraction and upgrading (shares of various oil sand technologies by energy)				
Mining (4.4%)	**Mining and upgrading (56.5%)**	***In situ* (32.9%)**	***In situ* and upgrading (6.2%)**	**Conventional crude**
92.6%	80.6%	83.1%	74.2%	98%

Vented, flaring, and fugitive emissions (g/MMBtu of crude)		
Factor	**VFF CH_4**	**VFF CO_2**
Venting emission factor	103	30
Flaring emission factor	0.5	89
Fugitive emission factor	4	0.2
Total VFF emission factor	108	120

Refinery process fuel use for major fuel products ($Btu_{process\ fuel}/MMBtu_{fuel\ product}$)			
Process Fuel	**Gasoline**	**Diesel**	**LPG (Propane)**
NG	62,837	52,173	44,506
Still gas – combustion	92,594	58,069	61,176
Electricity	4,019	3.24	2,966
H_2	6,334	13.0	7,104
Catalytic coke combustion	22,500	8,740	28,212

A.2 CORN-BASED ETHANOL

Figure A.2 illustrates basic production steps for making ethanol fuel from corn.

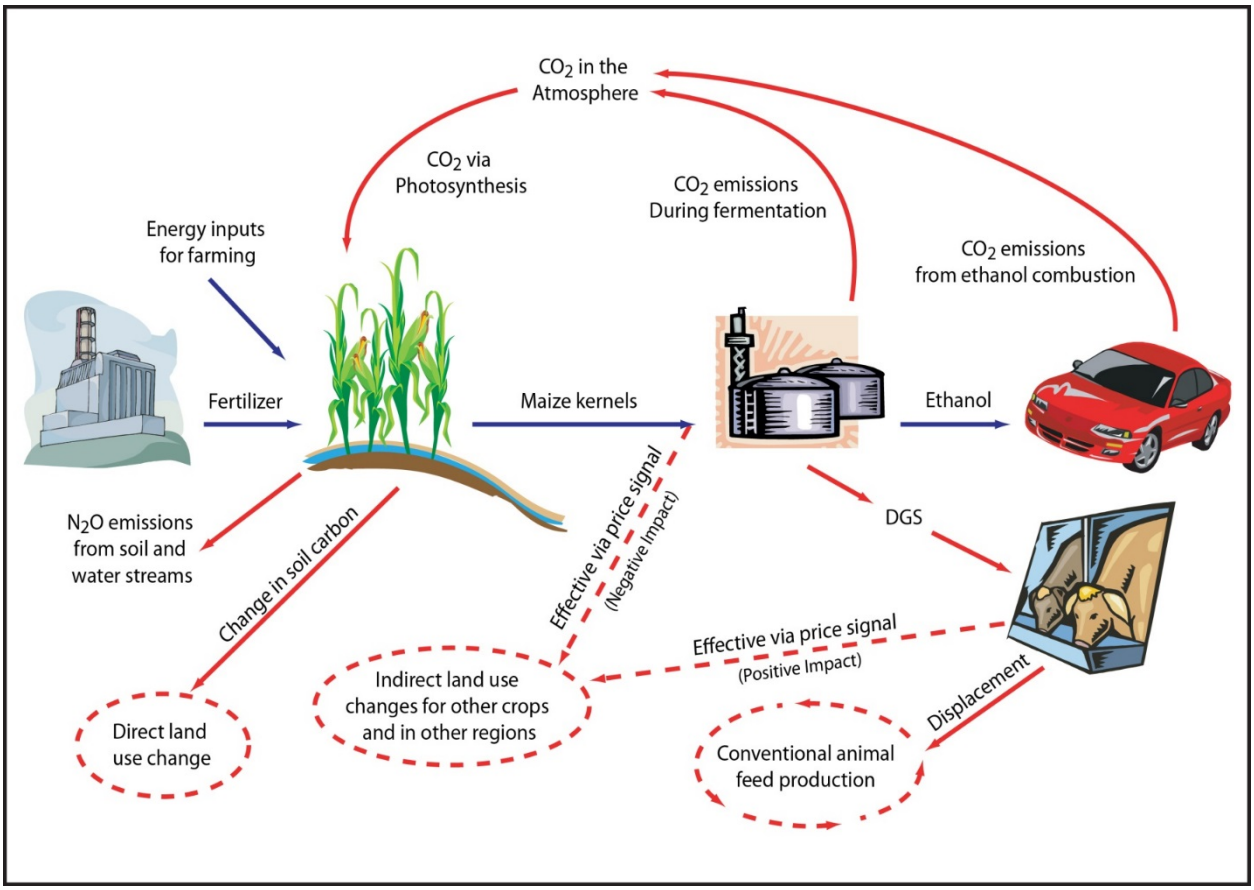

Figure A.2. Corn ethanol fuel cycle

Our analysis of corn-based ethanol includes farming, production of ethanol, and combustion from end-use. The farming component includes:

- Average energy consumption for corn farming (including planting, maintenance, collection, storage, and transport to processing facilities),
- Fertilizer and chemical use,
- N_2O released from above- and belowground biomass, and
- GHG emissions associated with LUC.

The analysis of ethanol production at dry and wet mills includes:

- Ethanol yield at dry mill and wet mill plants,
- Share of dry mills in total ethanol production,
- Average energy use for ethanol production in dry and wet mill plants, and
- Co-product yield (DGS).

The GREET 2014 estimates for the above parameters are provided in the following table:

Corn ethanol production parameters	
Parameter	**GREET 2014 Estimate**
Corn farming (per bushel of corn except as noted) – 2015	
Energy use for corn farming	9,142 Btu
N fertilizer application	402.8 g
P_2O_5 fertilizer application	138.7 g
K_2O fertilizer application	144.0 g
Limestone application	1,094 g
N_2O conversion rate of N fertilizer	1.525%
NG use per ton of ammonia produced	31,384 MMBtu
Corn ethanol production (dry mill plants) – 2015	
Ethanol yield (without oil extraction)	2.86 gal/bushel of corn
Ethanol plant energy use (without oil extraction)	26,856 Btu/gal of ethanol
DGS yield (without oil extraction)	5.63 dry lb/gal of ethanol
Ethanol yield (with oil extraction)	2.88 gal/bushel of corn
Ethanol plant energy use (with oil extraction)	26,421 Btu/gal of ethanol
DGS yield (with oil extraction)	5.39 dry lb/gal of ethanol
Corn oil yield (with oil extraction)	0.19 dry lb/gal of ethanol
Share of Dry Mill Plants with Oil Extraction	80%
Corn ethanol production (wet mill plants)	
Ethanol yield	2.67 gal/bushel of corn
Ethanol plant energy use	47,409 Btu/gal of ethanol
Share of ethanol production from wet mill plants	11.4%
Enzyme and yeast assumptions	
Enzyme use	0.001 ton/dry ton of corn
Yeast use	0.000358 ton/dry ton of corn

The GHG emissions attributed to LUC in GREET 2014 is 611 g CO_2e/gal of ethanol.

A.3 BIO-BASED GASOLINE AND DIESEL

Figure A.3 illustrates basic production steps for making gasoline and diesel biofuels.

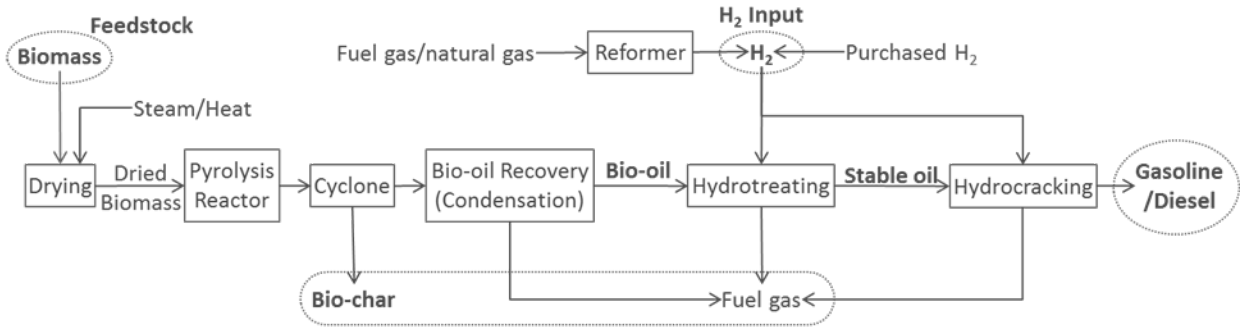

Figure A.3. Bio-based gasoline and diesel production steps

Our analysis of bio-based gasoline and diesel includes pyrolysis of biomass (forest residue), oil recovery, and hydrogen treatment of the pyrolysis oil. For the biomass feedstock, GREET accounts for the energy use for collecting logging residue and forest thinning. The key input for forest residue collection is the average energy consumption to collect stover or forest residue. The pyrolysis and stabilization of pyrolysis oil includes:

- Yield of main product of pyrolysis process (oil) and
- Hydrogen use for hydrotreatment and stabilization of pyrolysis oil.

The GREET 2014 estimates for the above parameters are provided in the following table:

Biofuel production parameters	
Parameter	**GREET 2014 Estimate**
Energy use for collection	132,180 Btu/dry ton
Pyrolysis/stabilization process	
Biomass inputs	3.19 dry lb/lb stable oil
Electricity use	737 Btu/lb stable oil
NG for supplemental H_2	2,871 Btu/lb stable oil

A.4 GTL Fischer-Tropsch Diesel

Figure A.4 illustrates basic production steps for making FTD from NG.

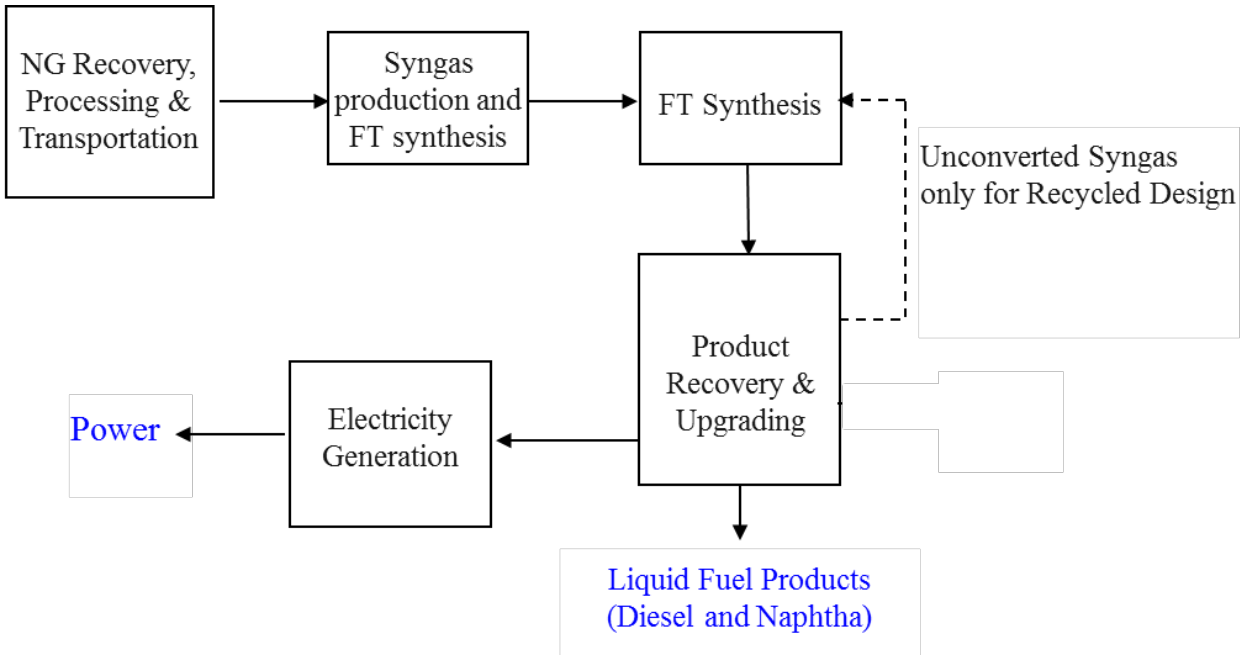

Figure A.4. FTD production from NG

Evaluation of the conversion of NG to FTD production includes:

- FTD production efficiency,
- Amount of co-produced electricity, and
- Energy required for CCS.

The GREET 2014 estimates for the above parameters are provided in the following table:

GTL FTD production parameters	
Parameter	**GREET 2014 Estimate**
FTD production efficiency	61.5%
Amount of coproduced electricity	4.16 kWh / MMBtu of FTD
Energy for CCS	335 kWh per ton of C captured
Carbon capture ratio	90%

A.5 SOY-DERIVED FAME AND HRD

Figures A.5 and A.6 illustrate basic production steps for making FAME and HRD fuels, respectively, from soybeans.

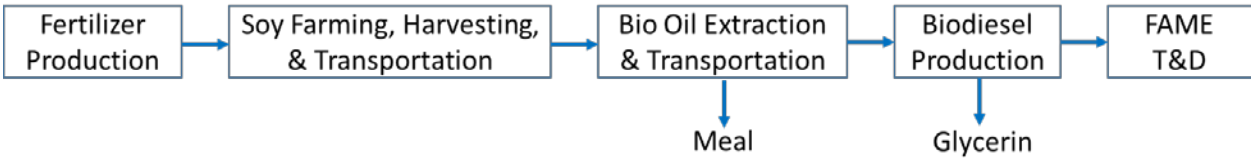

Figure A.5. FAME biodiesel production pathway from soybeans

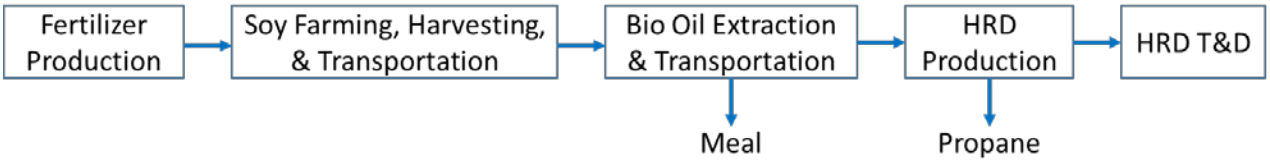

Figure A.6. HRD production pathway from soybeans

As with our analysis of corn-based products, our analysis of soy-based FAME and HRD fuels includes farming and production components. For soybean farming, we account for:

- Average energy consumption for soy farming (including planting, maintenance, collection, storage, and transport to processing facilities),
- Fertilizer and chemical use,
- N_2O released from above and below ground biomass, and
- GHG emission associated with LUC.

The bio-oil production pathway includes:

- Oil/soy ratio (yield),
- Meal/soy ration (co-product), and
- Oil extraction energy.

Similarly, the FAME production pathway includes:

- FAME/oil ratio (yield),
- Glycerin/oil ratio (co-product), and
- Energy use for conversion.

Production of HRD includes:

- HRD/oil ratio (yield),
- Propane/oil ratio (co-product),
- Energy use for conversion, and
- Hydrogen use for hydroprocessing.

The GREET 2014 estimates for the above parameters are provided in the following tables:

HRD production parameters	
Parameter	**GREET 2014 Estimate**
Oil extraction	
Oil yield	4.7 dry lb soybeans/lb of oil
Meal yield	3.7 dry lb/lb of oil
HRD production (per lb of HRD)	
Oil use	1.174 lb
H_2 use	0.032 lb
NG use	84.05 Btu
Electricity use	93.83 Btu
Propane mix yield	1,096 Btu

FAME production parameters	
Parameter	**GREET 2014 Estimate**
Soybean crushing for soy oil production	
FAME yield	1.014 lb FAME/lb oil
Energy inputs	
NG	2,068 Btu/lb soy oil
Electricity	447 Btu/lb soy oil
Hexane	59 Btu/lb soy oil
#2 Fuel oil	16 Btu/lb soy oil
#6 Fuel oil	32 Btu/lb soy oil
Coal	1,018 Btu/lb soy oil
Biomass	32 Btu/lb soy oil
Landfill gas	16 Btu/lb soy oil
Total	3,687 Btu/lb soy oil
Soy oil transesterification for FAME production	
Energy inputs	
NG	373 Btu/lb FAME
Electricity	55 Btu/lb FAME
MeOH	785 Btu/lb FAME
Total	1,213 Btu/lb FAME
Glycerin yield	0.120 lb/lb FAME

GREET does not include LUC GHG modeling for FAME and HRD volume production from soybeans. For this study, GHG emissions from LUC for FAME and HRD production is assumed at 30 g CO_2e/MJ of FAME and HRD (as explained in Section 4.3.4).

A.6 CELLULOSIC ETHANOL

Figure A.7 illustrates basic production steps for making cellulosic ethanol.

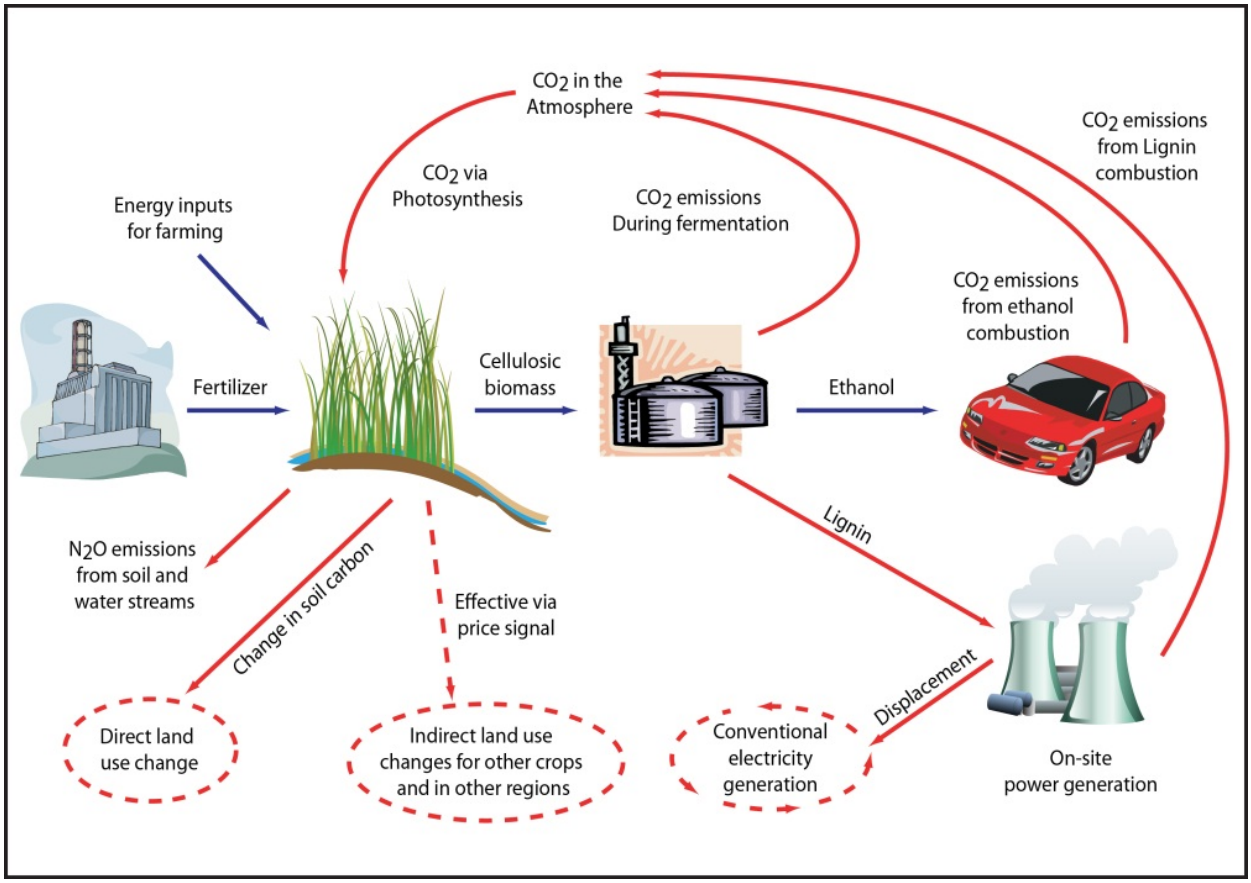

Figure A.7. Cellulosic ethanol fuel cycle

Our analysis of cellulosic ethanol includes farming, production of ethanol, and combustion from end-use. Corn stover collection includes:

- Average energy consumption for stover collection and loading and
- Supplemental (N, P, K) fertilizer use.

Calculations for the ethanol production via enzymatic process include:

- Ethanol yield,
- Amount of electricity exported from lignin combustion, and
- Consumption rates of enzymes and yeast.

The estimates for the above parameters in this study are provided in the following table:

Cellulosic ethanol parameters	
Parameter	**GREET 2014 Estimate**
Corn stover collection (per dry ton)	
Energy use for collection	192,500 Btu
Energy use by loader	42,000 Btu
Supplemental N fertilizer	7,000 g
Supplemental P fertilizer	2,000 g
Supplemental K fertilizer	12,000 g
Cellulosic ethanol production	
Ethanol yield	75 gal/ton
Electricity yield	2.9 kWh/gal
Enzyme use	0.010 dry ton/ton of substrate
Yeast use	0.00249 dry ton/ton of substrate

A.7 CNG

Figure A.8 illustrates basic processing steps for using CNG as a vehicle fuel.

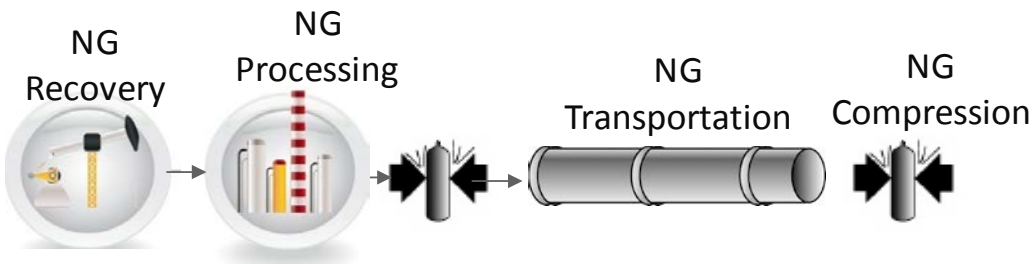

Figure A.8. CNG pathway

Our analysis of the CNG pathway includes conventional and shale gas recovery, processing, transportation, and compression. The key parameters in these stages are:

- Average energy efficiency for gas recovering,
- Energy efficiency for NG processing,
- Gas flaring, and
- CO_2 venting and CH_4 leakage.

The GREET 2014 estimates of energy efficiency are 97.2% for both recovery and processing. Estimates of CH_4 emissions are provided in the following table:

CH_4 emissions for the CNG pathway (%volumetric NG throughput)		
Stage	**Shale Gas**	**Conventional Gas**
Gas field (total)	0.37	0.30
Completion/workover	0.07	0.003
Unloading	0.05	0.05
Other sources	0.25	0.25
Processing	0.13	0.13
Transmission	0.39	0.39
Distribution	0.30	0.30
Total	1.19	1.13

A.8 U.S. AVERAGE GRID ELECTRICITY

Figure A.9 illustrates basic production steps for generating electricity for charging BEVs.

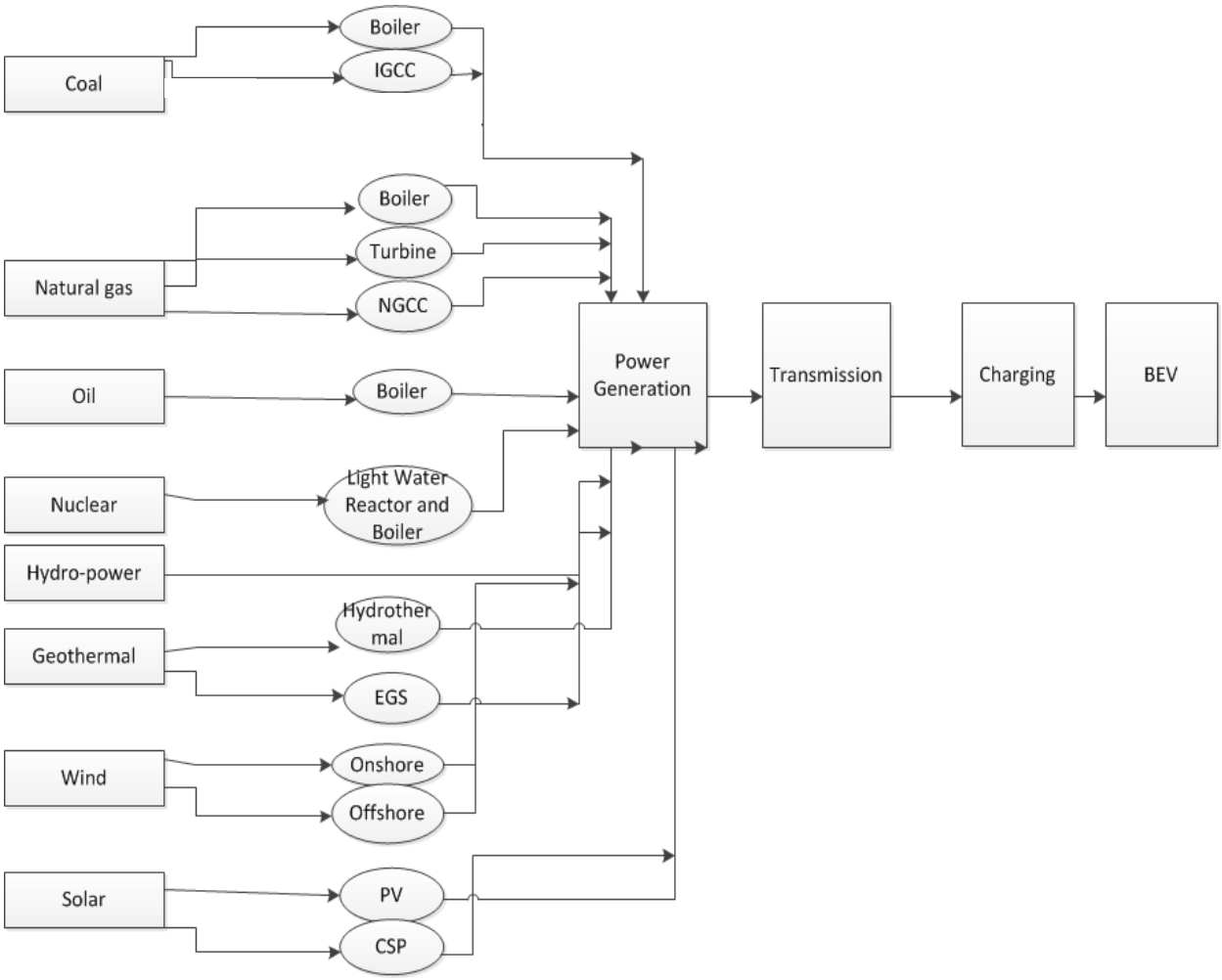

Figure A.9. Grid electricity generation cycle

Our analysis of electric power generation includes:

- 2014 average fuel mix for the U.S electrical grid,
- LHV-based electricity generation efficiency for fossil-fuel power plants, and
- Electricity transmission and distribution losses.

The GREET 2014 estimates for the above parameters are provided in the following tables:

Electrical grid generation mix (%)		
Fuel	**2014**	**2030**
Residual oil	0.8	0.8
NG	26.5	32.2
Coal	40.7	35.1
Nuclear power	18.6	16.2
Biomass	1.0	2.3
Other renewables	12.5	13.4

Generation efficiency and share within fuel types (%)				
Fuel	**Combustion Technology**	**Generation Energy Efficiency**		**Share of Generation for Each Fuel Type**
		2010	**2030**	
Coal	Steam cycle	34.7	38.0	99.9
	IGCC	34.8	45.0	0.1
NG	Steam cycle	32.3	36.0	11.5
	Combustion turbine	31.6	36.0	5.5
	ACC	50.6	60.0	82.1
	ICE	32.8	36.0	0.9
Oil	Steam cycle	33.0	37.0	77.2
	Combustion turbine	29.4	34.0	18.2
	ICE	36.3	40.0	4.6
Biomass	Steam cycle	21.9	25.0	100

GREET 2014 estimates the electricity transmission and distribution losses to be 6.5%.

A.9 HYDROGEN PATHWAYS

Figure A.10 illustrates basic hydrogen production pathway, and Figure A.11 illustrates hydrogen production from biomass.

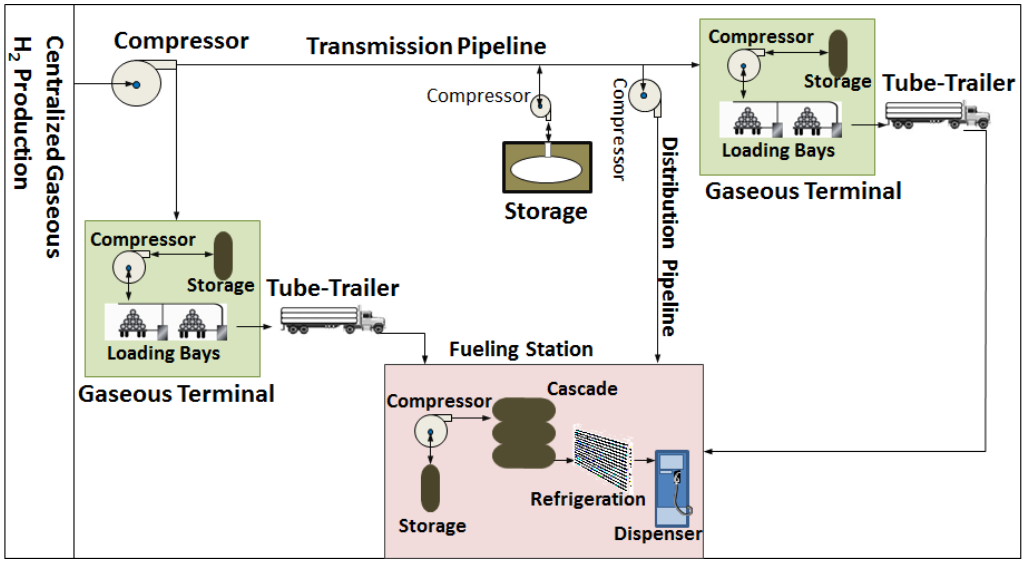

Figure A.10. Hydrogen fuel pathways

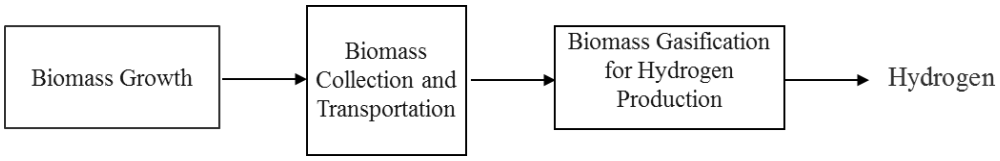

Figure A.11. Hydrogen production from biomass gasification

Our analysis of the hydrogen production pathways from NG and biomass gasification include:

- Hydrogen production efficiency from NG via SMR,
- Upstream emissions for NG production and transportation,
- Energy required for CCS,
- Efficiency of hydrogen production via biomass gasification, and
- Compression and precooling energy at refueling stations.

The GREET 2014 estimates for hydrogen production parameters are provided in the following table:

Hydrogen production parameters			
Parameter	**SMR w/o CCS**	**SMR w/ CCS**	**Biomass Gasification**
Production energy efficiency (not including CCS)	72.0%	72.2%	46.1%
CCS Energy	N/A	357 kWh/ton C	N/A

GREET 2014 estimates the electric energy consumption for hydrogen refueling to be 3.1 kWh/kg.

Appendix B: PRICE AND EFFICIENCY COMPARISON OF MODELED AND REAL-WORLD VEHICLES

This appendix details the price and efficiency of midsize vehicles currently on the retail market and compares them to those modeled in this report. Different vehicles have different uptakes of technology that change vehicle efficiency by improving weight, aerodynamics, or engine performance. Even among vehicles with nominally similar characteristics, this heterogeneity of vehicles can lead to large differences in price and fuel economy. Table B.1 shows fuel economy and manufacturer's suggested retail price (MSRP) for all MY2015 midsize vehicles, including conventional gasoline ICEVs, according to sales-weighted percentile. The "retail price" of real vehicles may include factors unrelated to component cost and is not directly analogous to the modeled RPE used in Section 6. Half of these vehicles have fuel economy ranging between 27 and 30 mpgge as determined per their EPA combined "window-stickers."[18] For ICE vehicles, the overall spread of fuel economies is smaller, and nearly all vehicles sold have fuel economy between 22 and 33 mpgge. The maximum fuel economy in Table B.1 (114 mpgge) is for a BEV.

Table B.1. Fuel economy and MSRPs for MY2015 midsize vehicles sold in 2015 in the United States

Sales-weighted Percentile	All Midsize Vehicles		Midsize ICE Vehicles	
	Fuel Economy (mpgge)	MSRP (2015$)	Fuel Economy (mpgge)	MSRP (2015$)
Minimum	19	$15,900	19	$15,890
5th percentile	23	$16,200	22	$16,200
25th percentile	27	$17,200	25	$17,000
50th percentile	27	$22,100	27	$22,100
75th percentile	30	$23,000	30	$22,500
95th percentile	41	$37,700	33	$37,700
Maximum	114	$120,400	34	$112,500

Figure B.1 shows the fuel economy and price for 67 MY2015 midsize makes and models as compared to the modeled vehicles in this report. In this figure, the base MSRP of vehicles sold within calendar year 2015 are plotted against their fuel economies (Ward's Auto 2016). Each point represents a single model, and its size represents the number of vehicles sold. Gasoline, diesel, HEV, PHEV10/20, and BEV90 vehicles were included in this data set, each represented by a different color in the figure.

The plot also includes the fuel economies and costs of CURRENT TECHNOLOGY, HIGH VOLUME vehicles modeled in this report from Sections 6.3 and 6.5, labeled with X's and colors corresponding to their respective drivetrains. In the real world, fuel economy may vary; vehicle models are meant to be a generic model rather than representing a specific vehicle. The modeled vehicles approximate actual vehicles for cost and fuel economy for each drivetrain, even if they do not exactly matching a single real-world vehicle. Although the fuel economy of newer vehicle technologies is more difficult to accurately model,

[18] Over one-quarter of the midsize vehicle sales market, including three of the five best-selling vehicles, have EPA window-sticker fuel economies of 27 mpgge, resulting in the 25th and 50th percentiles being identical. Window sticker fuel economy corresponds to the on-road fuel economy for the modeled vehicles in this report.

the fuel economy of the modeled H_2 FCEV midsize vehicle falls within the range of values for commercially available MY2016 vehicles of different size classes.[19]

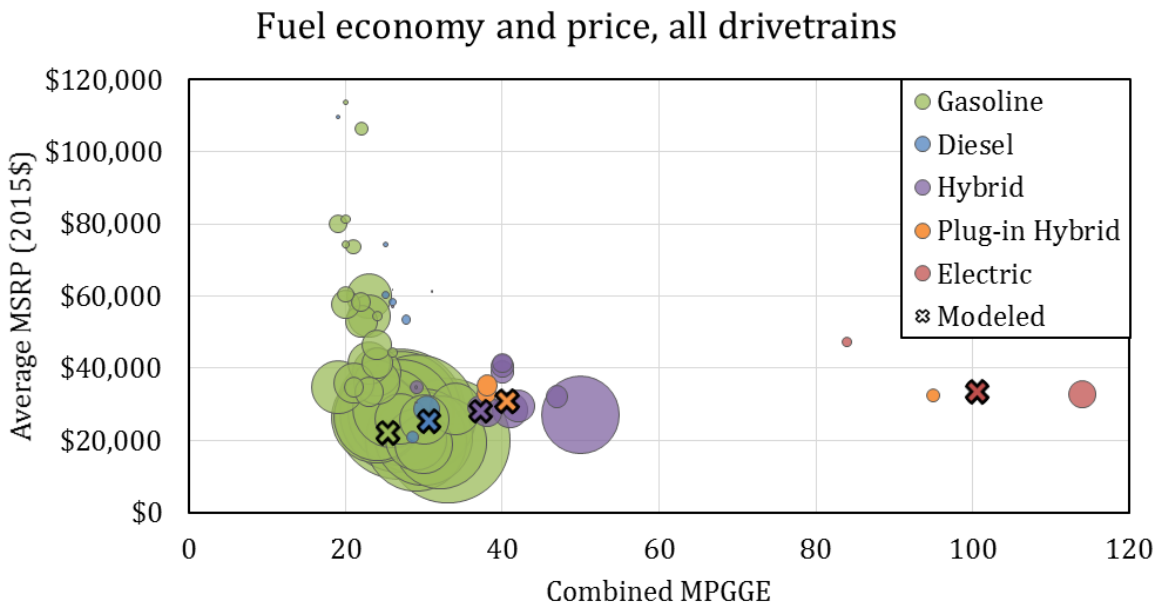

Figure B.1. Fuel economy and price for midsize vehicles sold in 2015

Figure B.2 highlights the variation within a single drivetrain with the case of gasoline-fueled SI ICEVs. In Figure B.2, each color represents a sales segment. The modeled CURRENT TECHNOLOGY ICE vehicle in this report (gray X) is most similar to cars from the "middle" segment in both price and fuel economy, but even in this segment, fuel economy variations of 25% exist between cars.[20]

[19] The Hyundai Tucson is a small SUV rated at 50 mpgge and the Toyota Mirai is a subcompact car rated at 66 mpgge. The Tucson is available for lease and the Mirai is available for purchase.

[20] While the EPA size class for all vehicles analyzed here corresponds to a midsize vehicle, Ward's Auto has further segmentation to differentiate these from a sales perspective. Here "small" corresponds to vehicles with a typical length under 180 in., "middle" corresponds to vehicles with a length under 195 in., and 'luxury' refers to models determined to be more luxurious than a typical car.

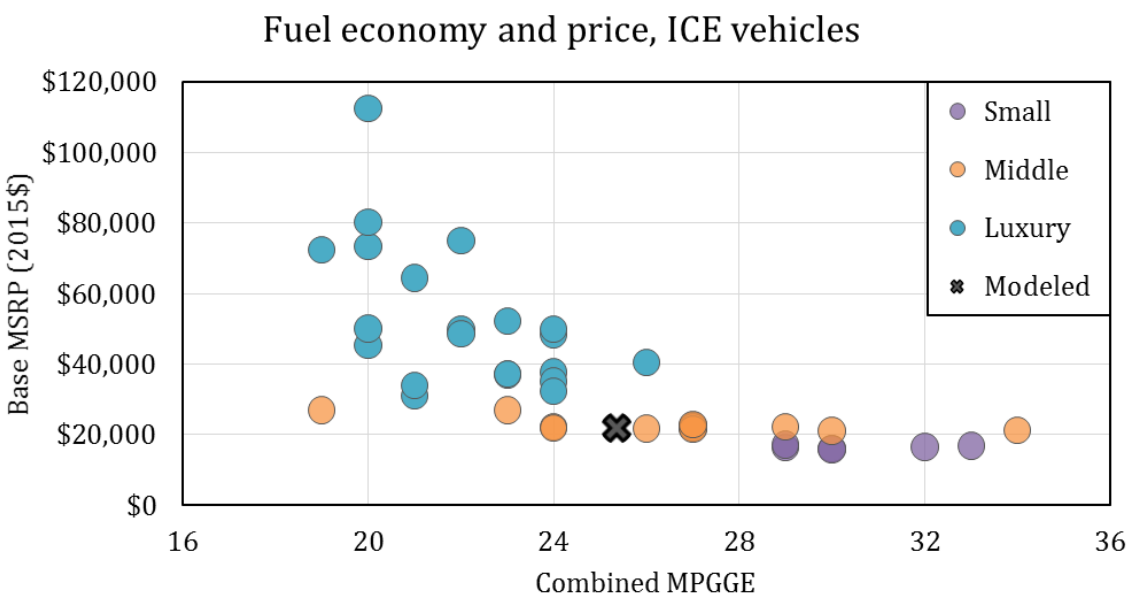

Figure B.2. Fuel economy and price for midsize ICEVs sold in 2015

Appendix C: GHG EMISSIONS FOR DIFFERENT VEHICLE-FUEL PATHWAYS

This appendix details the total modeled emissions for different vehicle-fuel pathways in grams of CO_2 equivalent per vehicle-mile driven (g CO_2e / mi). As discussed in Section 2, GREET examines both the vehicle cycle and the fuel cycle to find the net emissions. Figures C.1–C.5 offer a breakdown of total lifecycle emissions by feedstock, fuel, tailpipe, and vehicle manufacturing. Bars extending below the axis represent reductions in the total GHG emissions due to biogenic CO_2 in the fuel offsetting the tailpipe emissions.

Figures C.6 and C.7 show the GHG emissions associated with vehicle manufacturing cycle in tonnes of CO_2e for each vehicle technology for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, respectively.

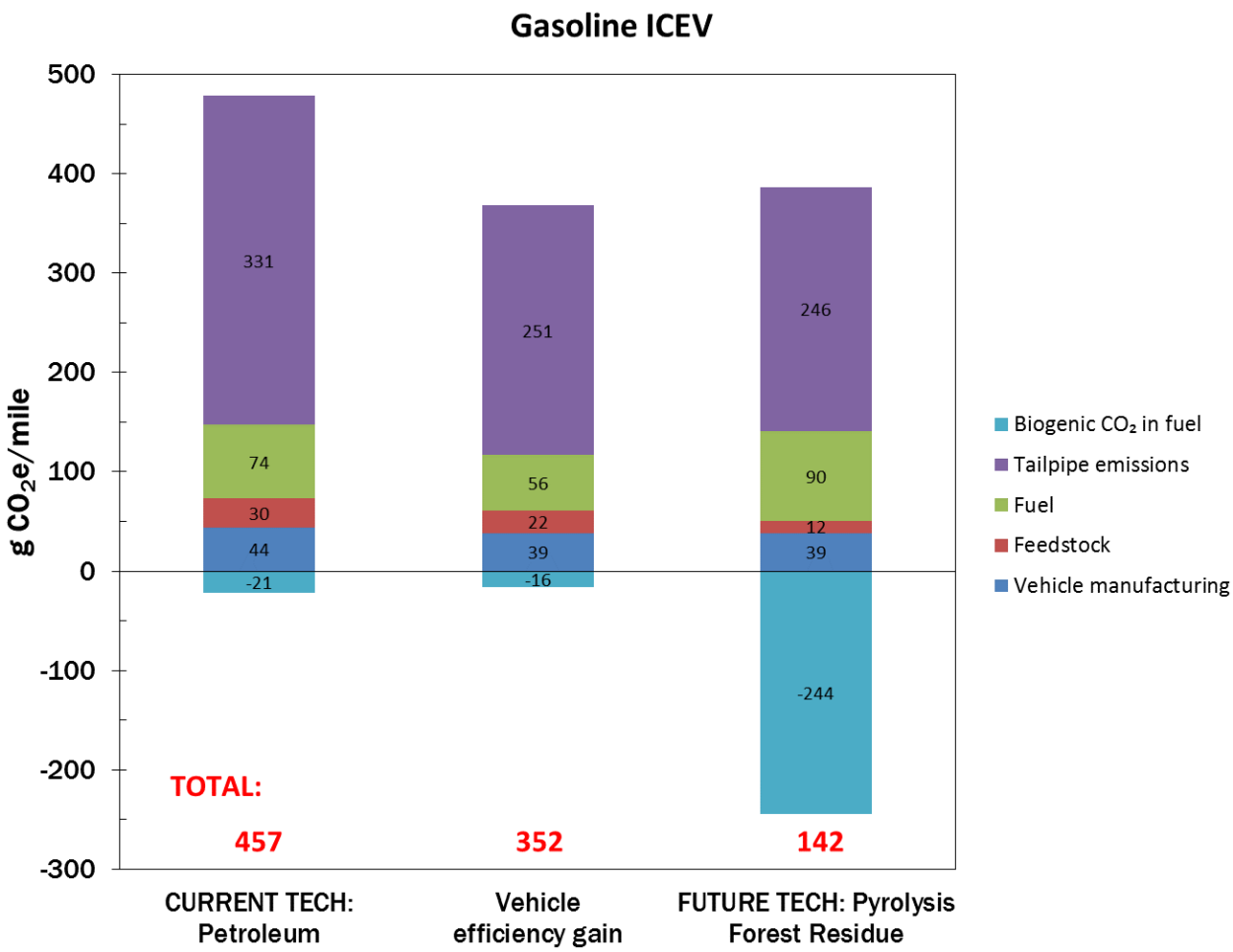

Figure C.1. Emissions for ICEV with gasoline sourced from petroleum and forest residue pyrolysis

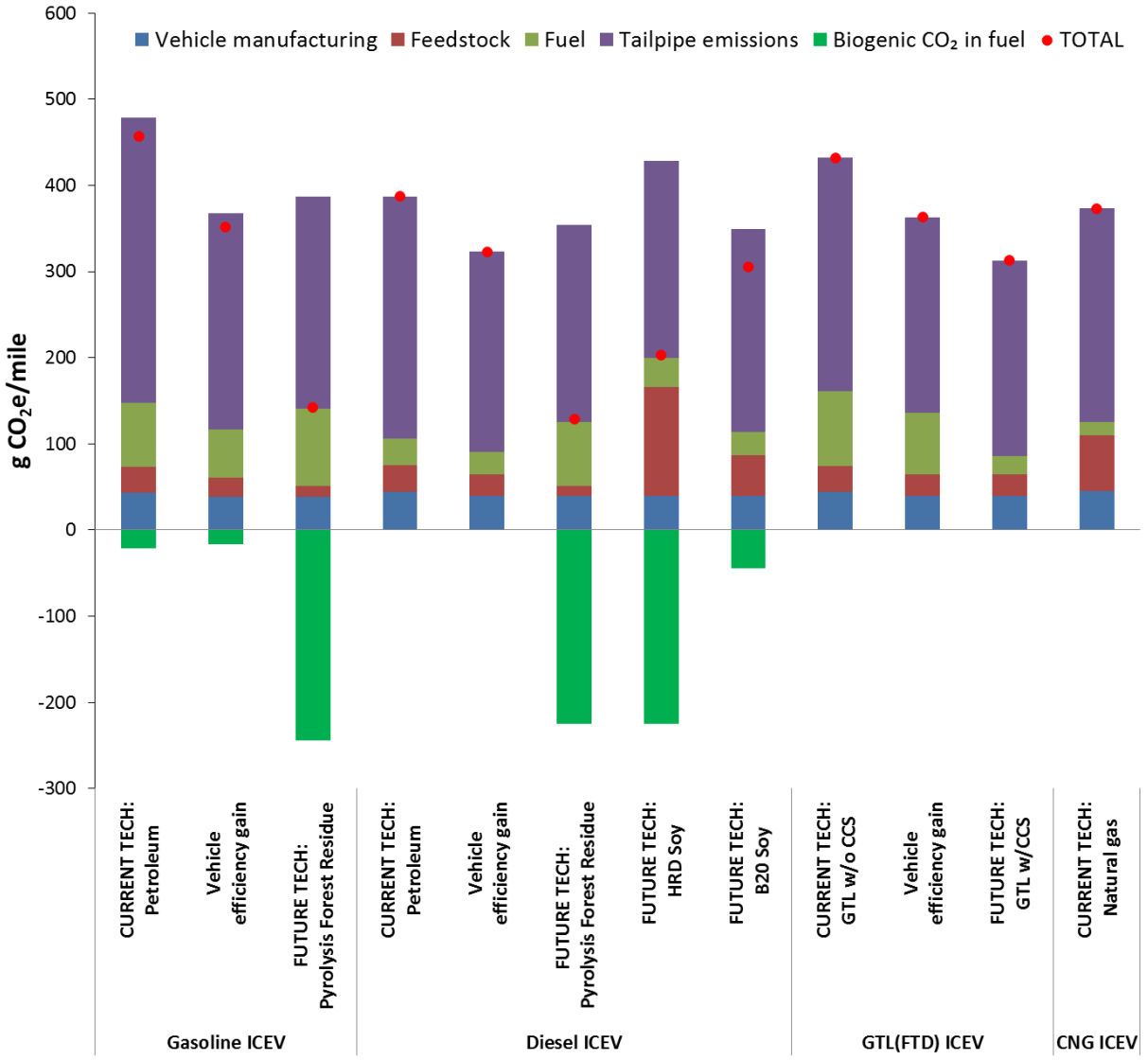

Figure C.2. Emissions for multiple gasoline, diesel, and NG ICEV pathways compared with gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

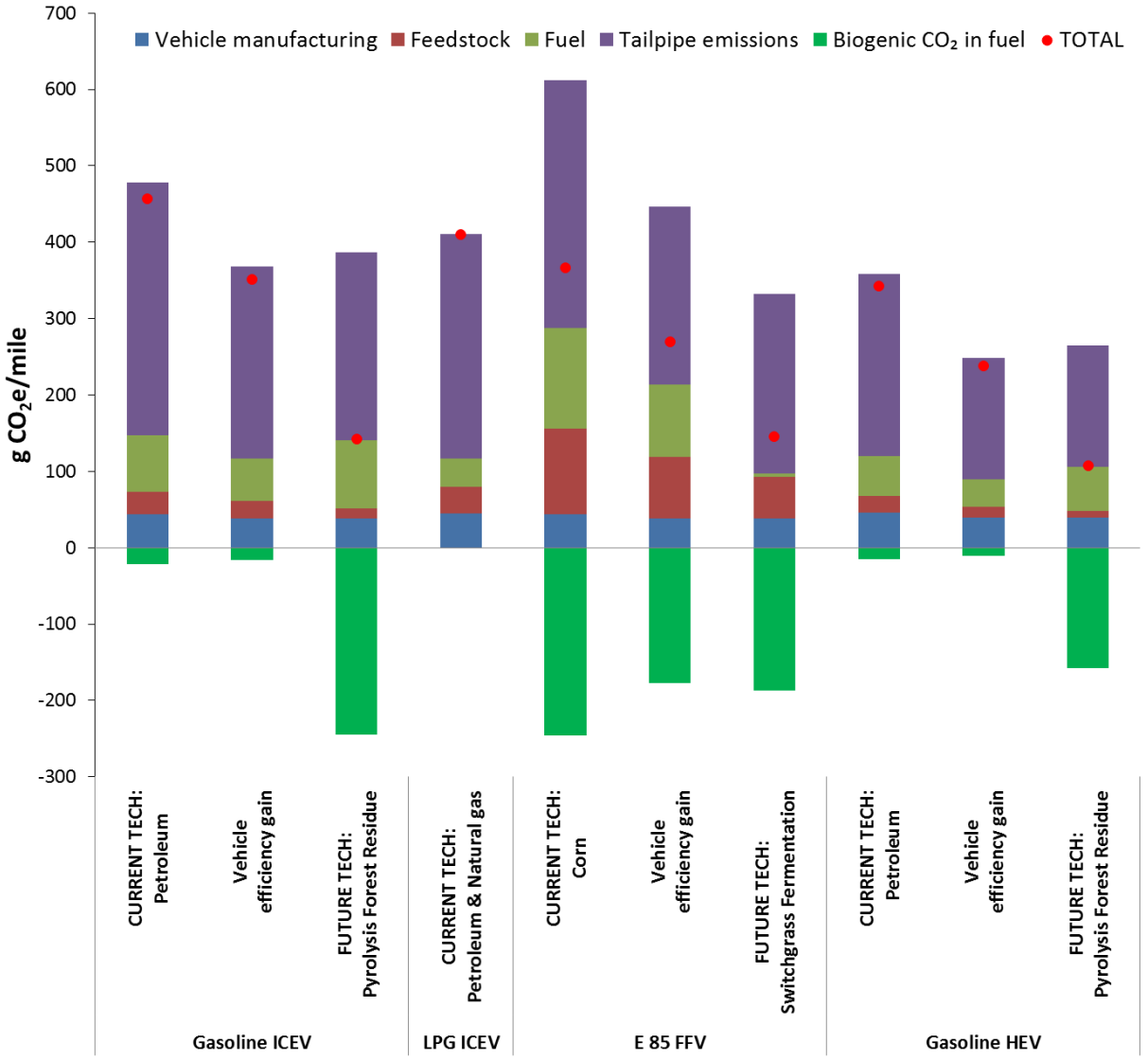

Figure C.3. Emissions for LPG ICEVs, E85 FFVs, and gasoline HEVs compared with gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

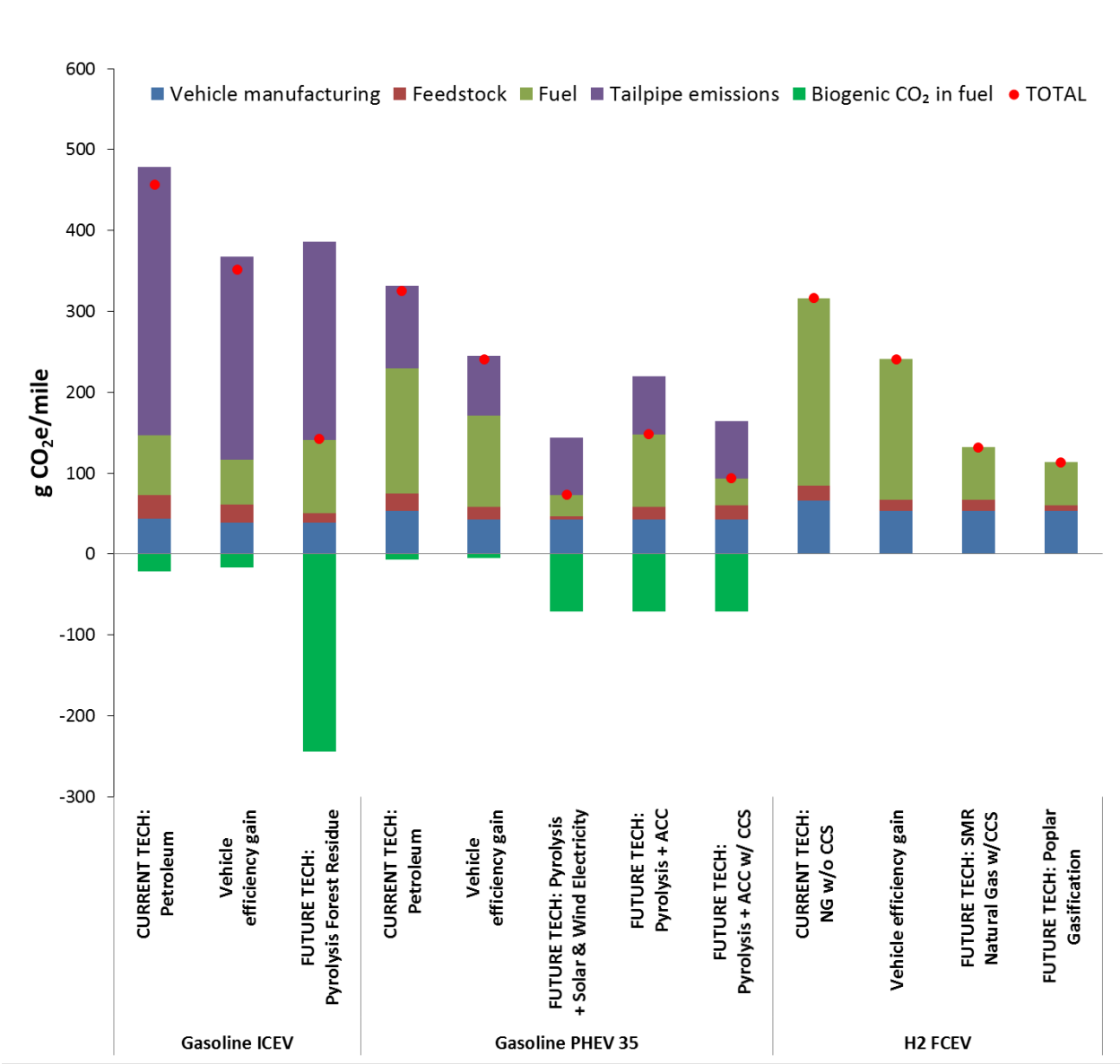

Figure C.4. Emissions for gasoline PHEV35 and H_2 FCEVs compared with gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

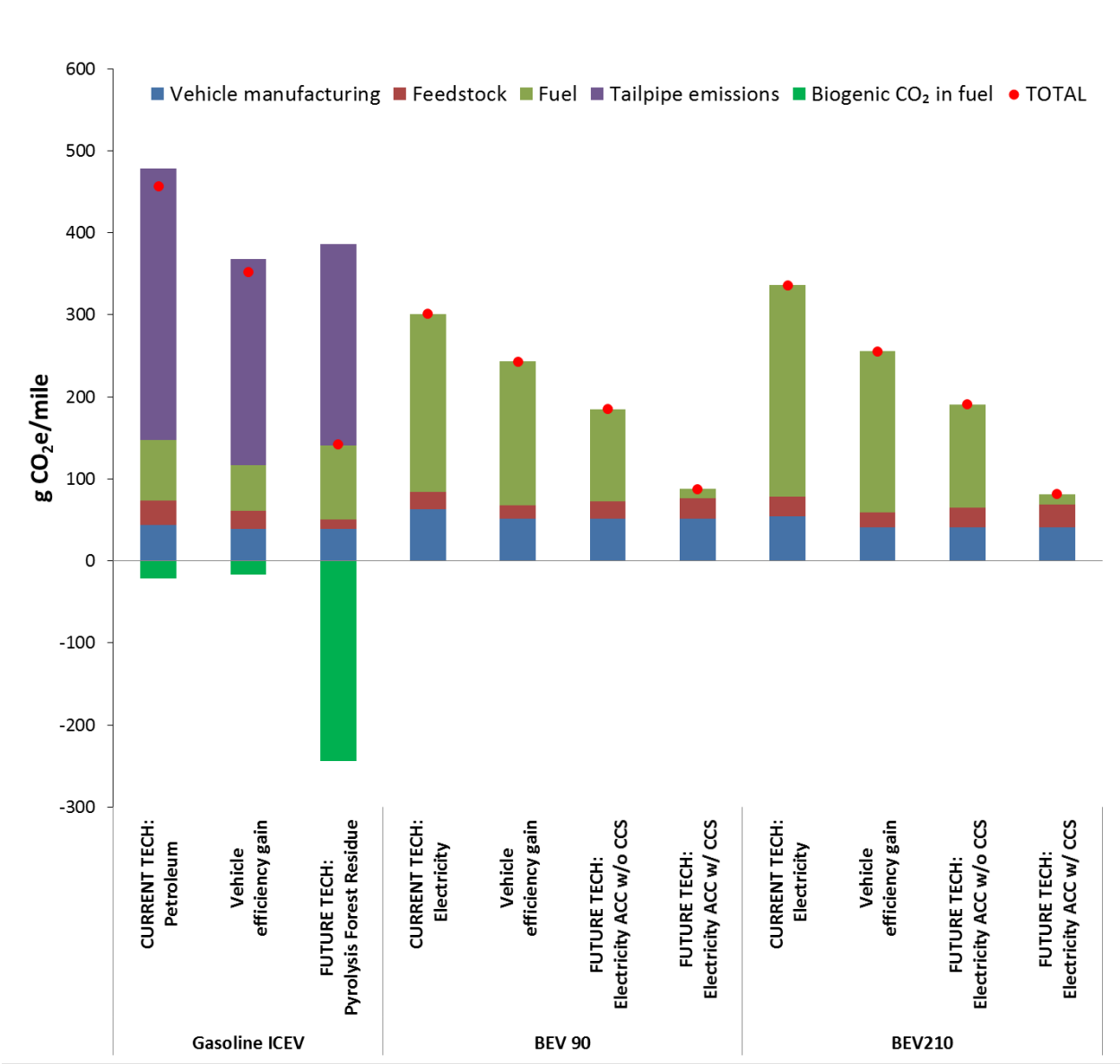

Figure C.5. Emissions for advanced BEV pathways compared with gasoline ICEV CURRENT TECHNOLOGY and efficiency gains

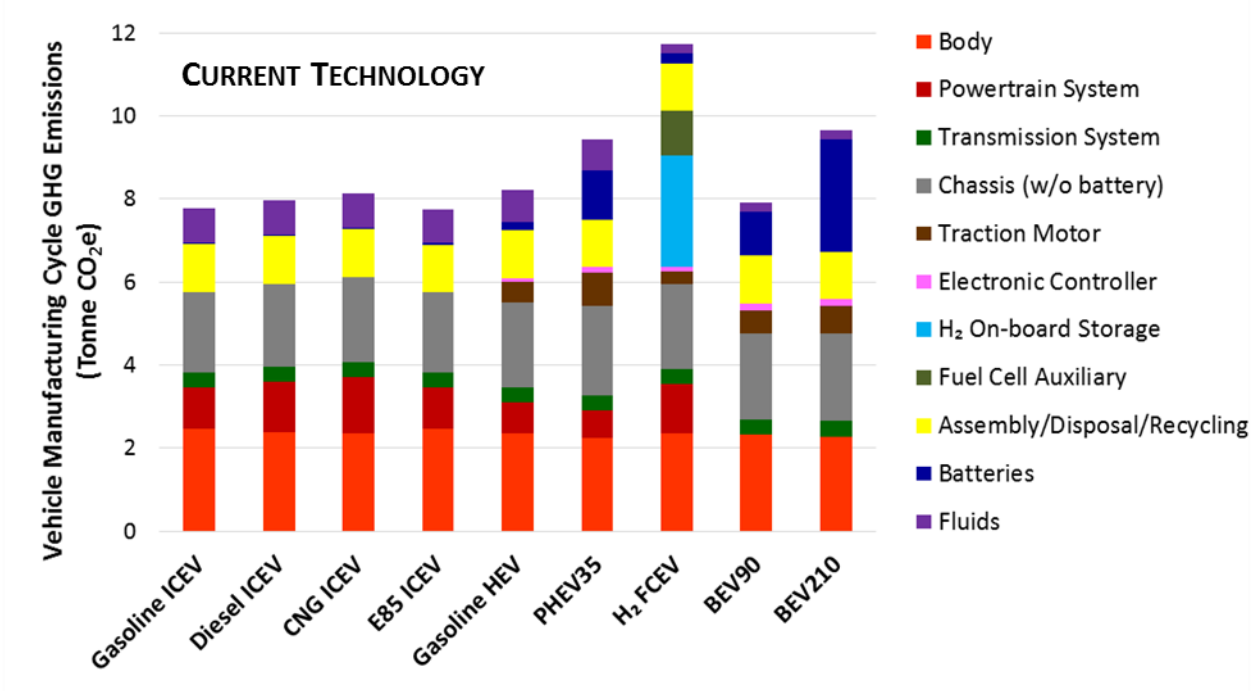

Figure C.6. Vehicle cycle GHG emissions by vehicle component for the CURRENT TECHNOLOGY case

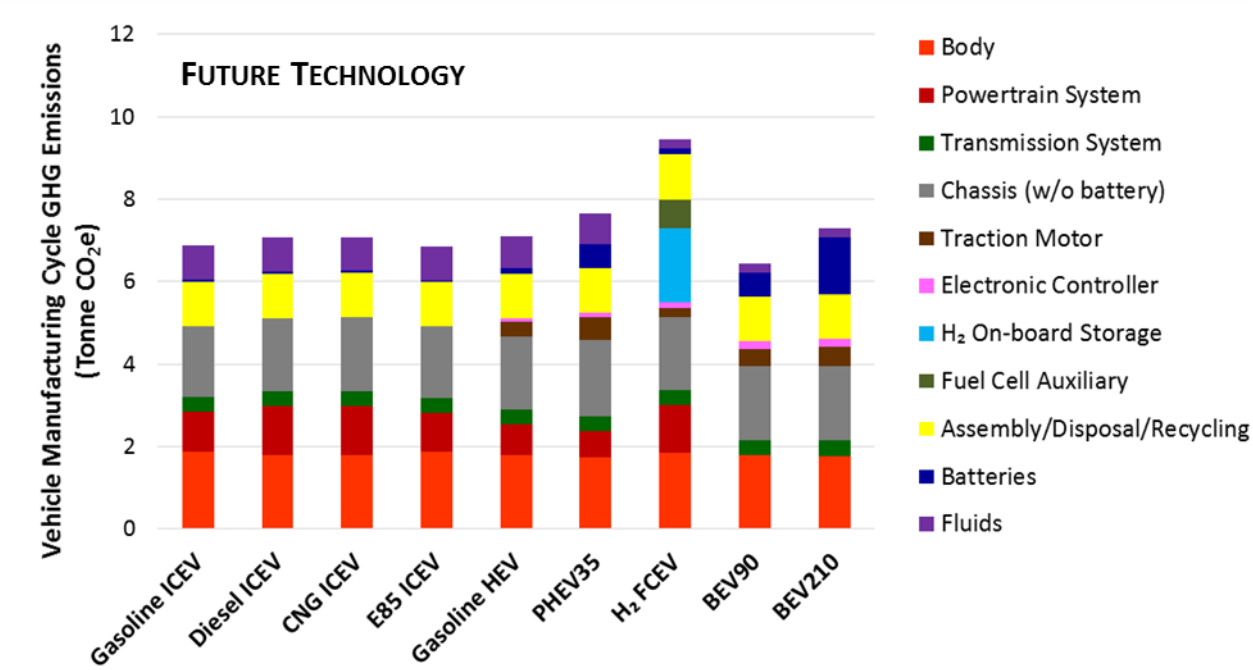

Figure C.7. Vehicle cycle GHG emissions by vehicle component for the FUTURE TECHNOLOGY case

Appendix D: Sensitivity of GHG Emission Projections to Key Vehicle-Fuel Parameters

Figures D.1–D.34 in this appendix show how sensitive the projected emissions for each pathway are to key input parameters. The central axis represents the baseline GHG emissions for the vehicle-fuel combination and the horizontal orange and blue lines show how the pathway GHG emissions change with a -3% and +3% change to each input, respectively.[21]

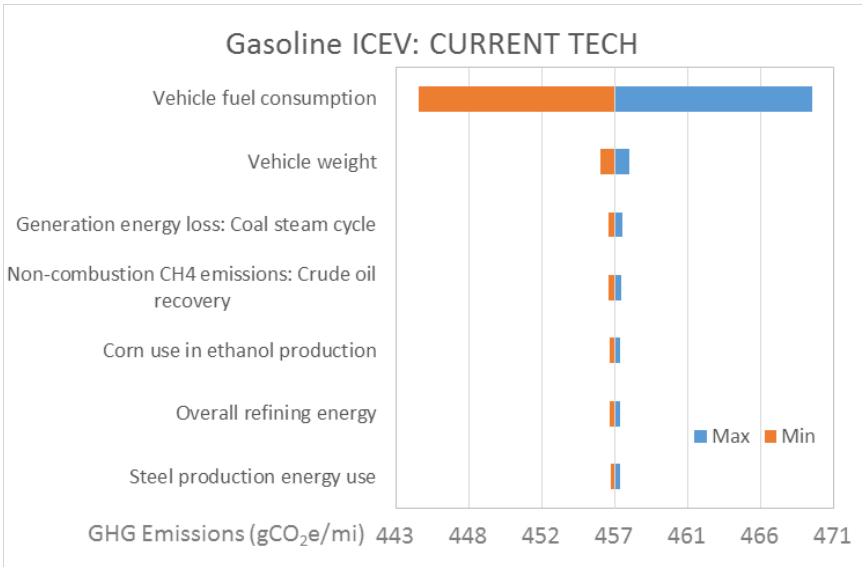

Figure D.1. Changes in GHG emissions for a 3% perturbation in each key parameter for Current Technology gasoline ICEV

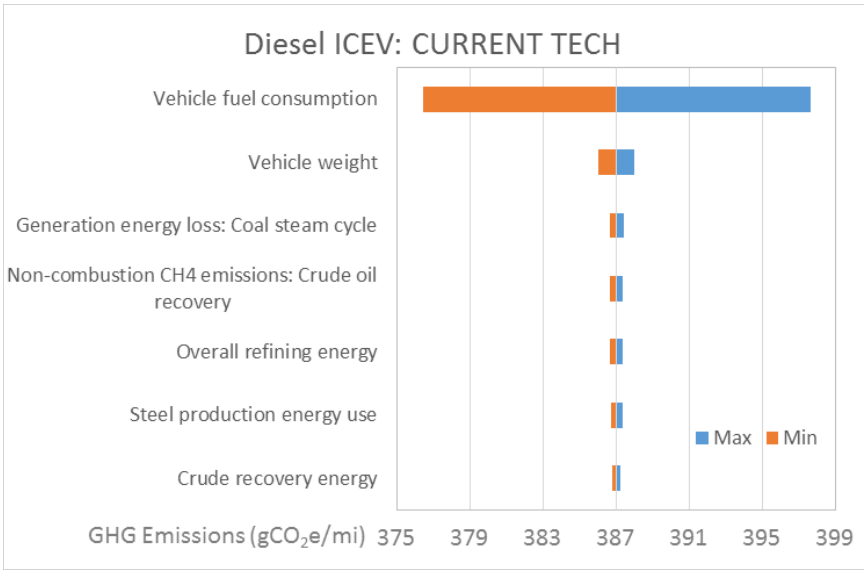

Figure D.2. Changes in GHG emissions for a 3% perturbation in each key parameter for Current Technology diesel ICEV

[21] In the case of E85 FFVs (Figures D.6 and D.18), the DGS and electricity yields are co-products rather than energy or material use. Thus, these are credits rather than a burden, resulting in reversal of the color bars.

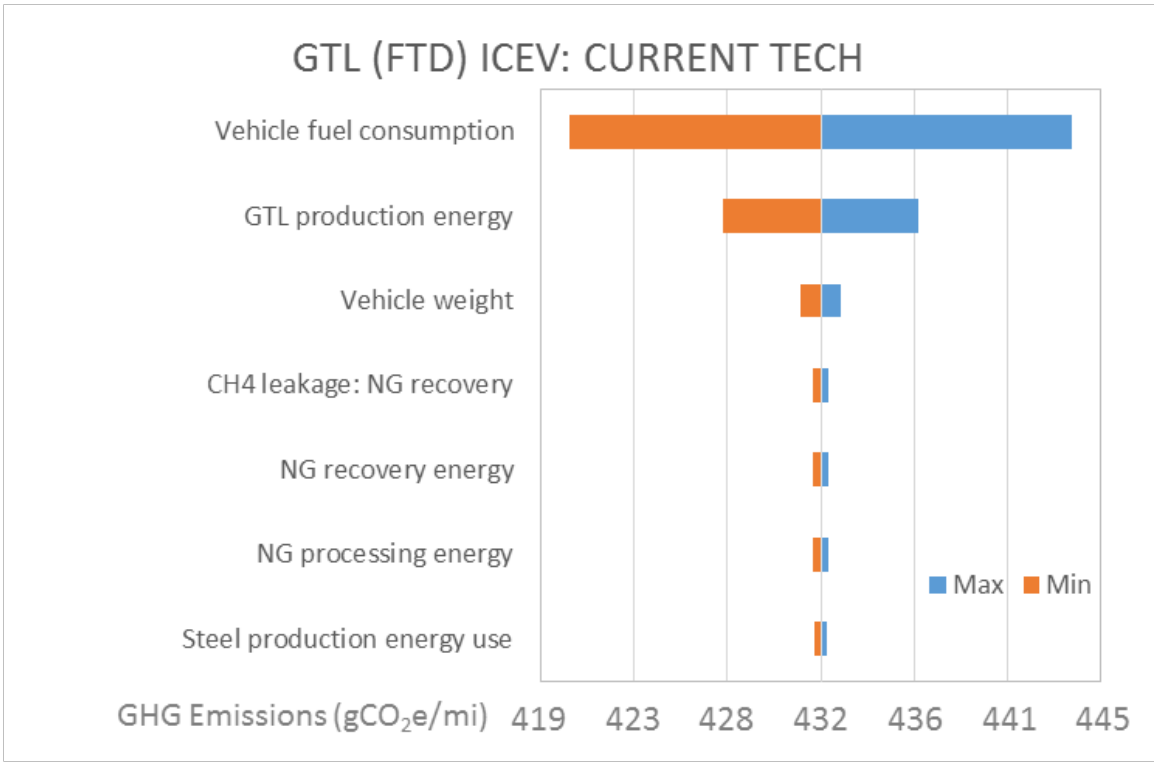

Figure D.3. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY diesel ICEV – GTL FTD

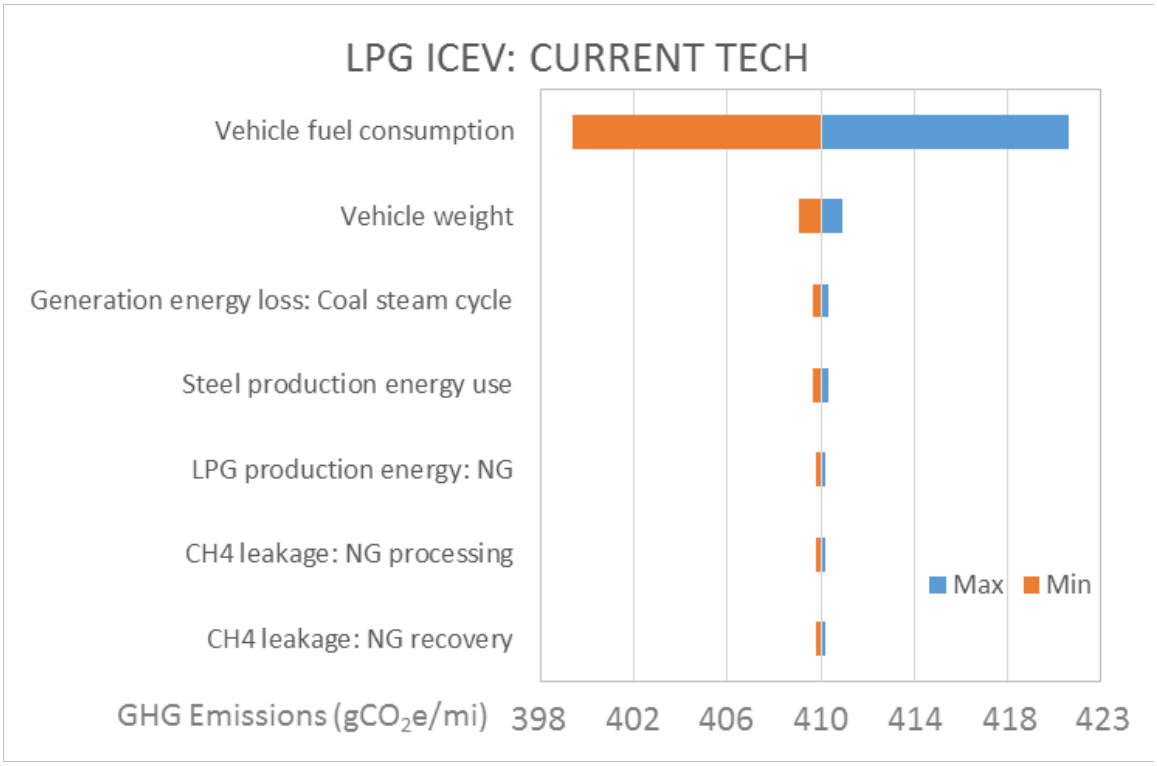

Figure D.4. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY LPG ICEV

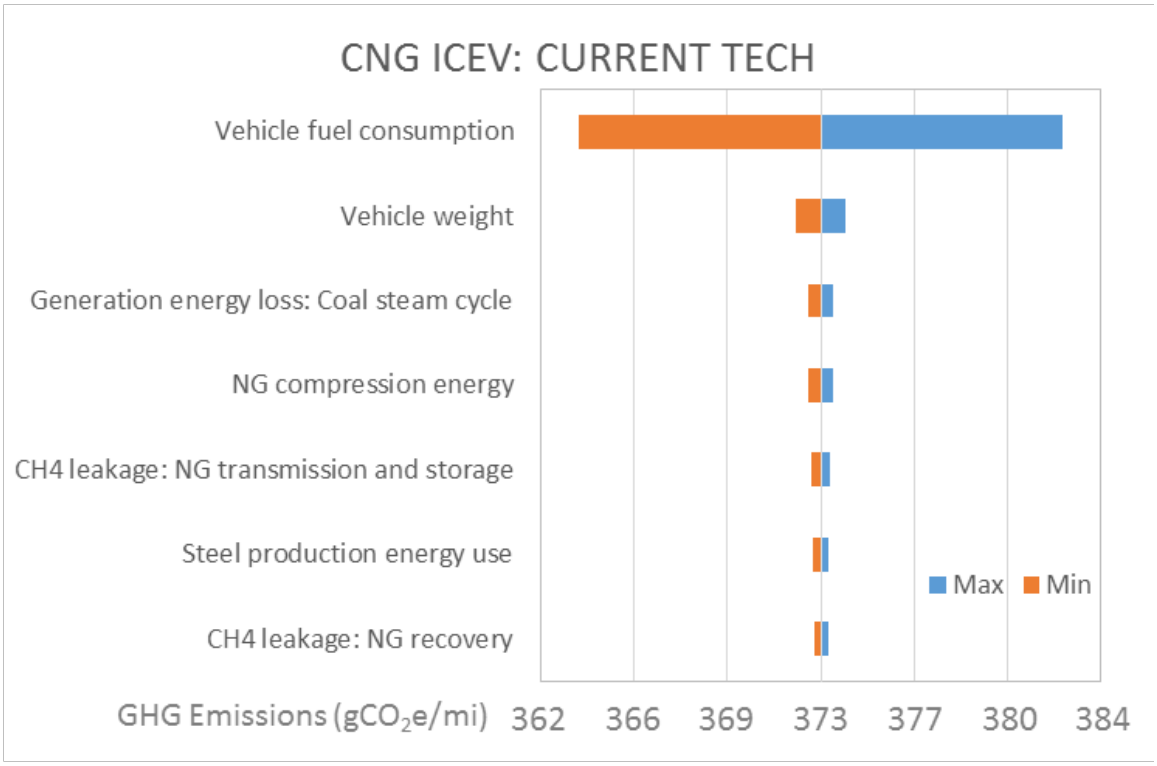

Figure D.5. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY CNG ICEV

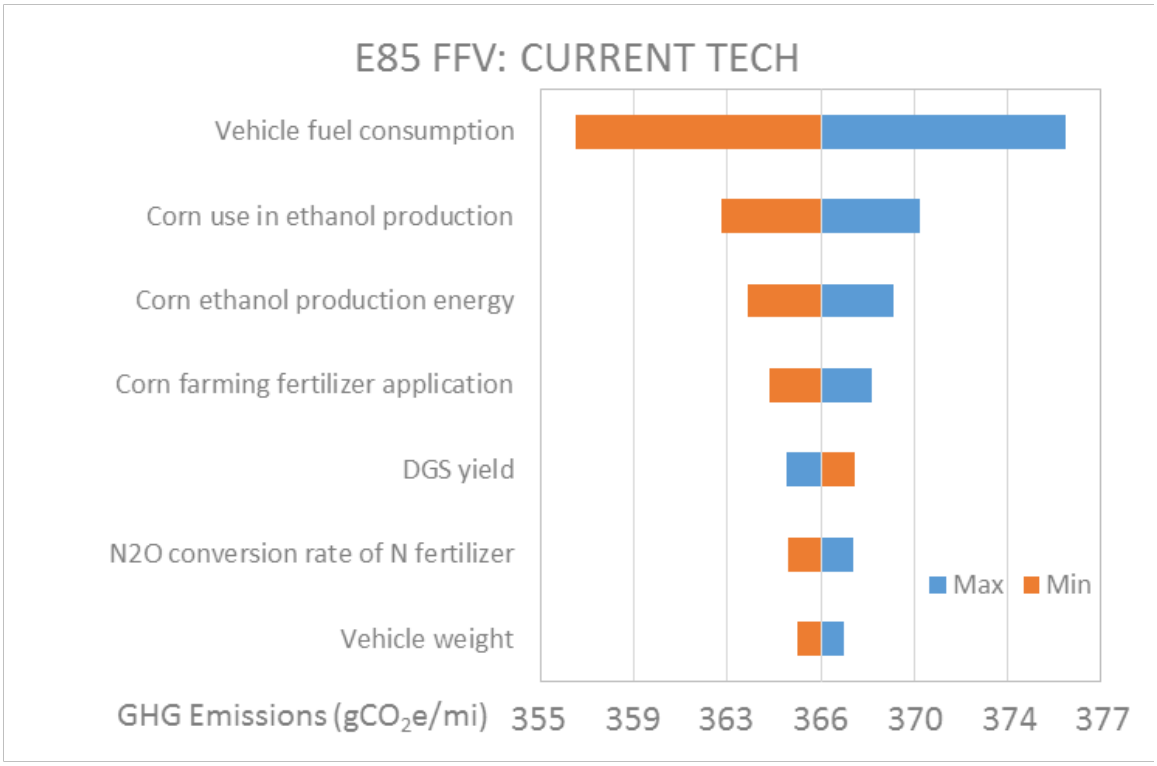

Figure D.6. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY E85 FFV

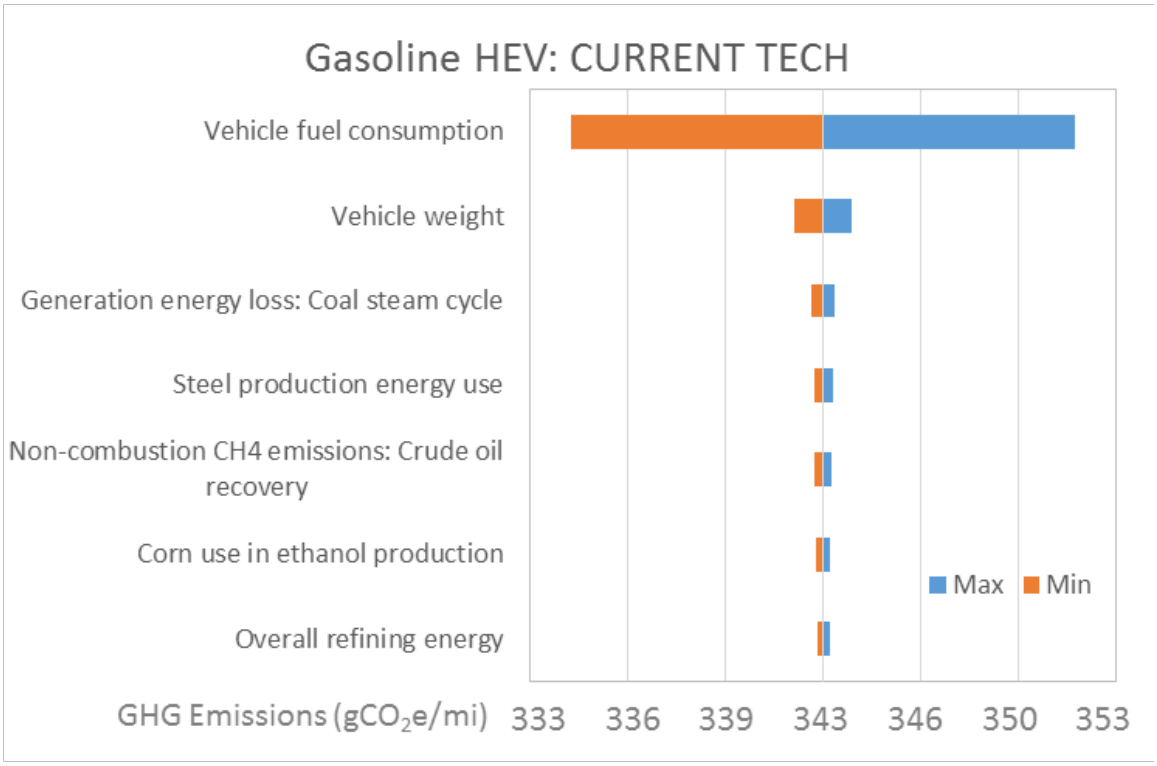

Figure D.7. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY gasoline HEV

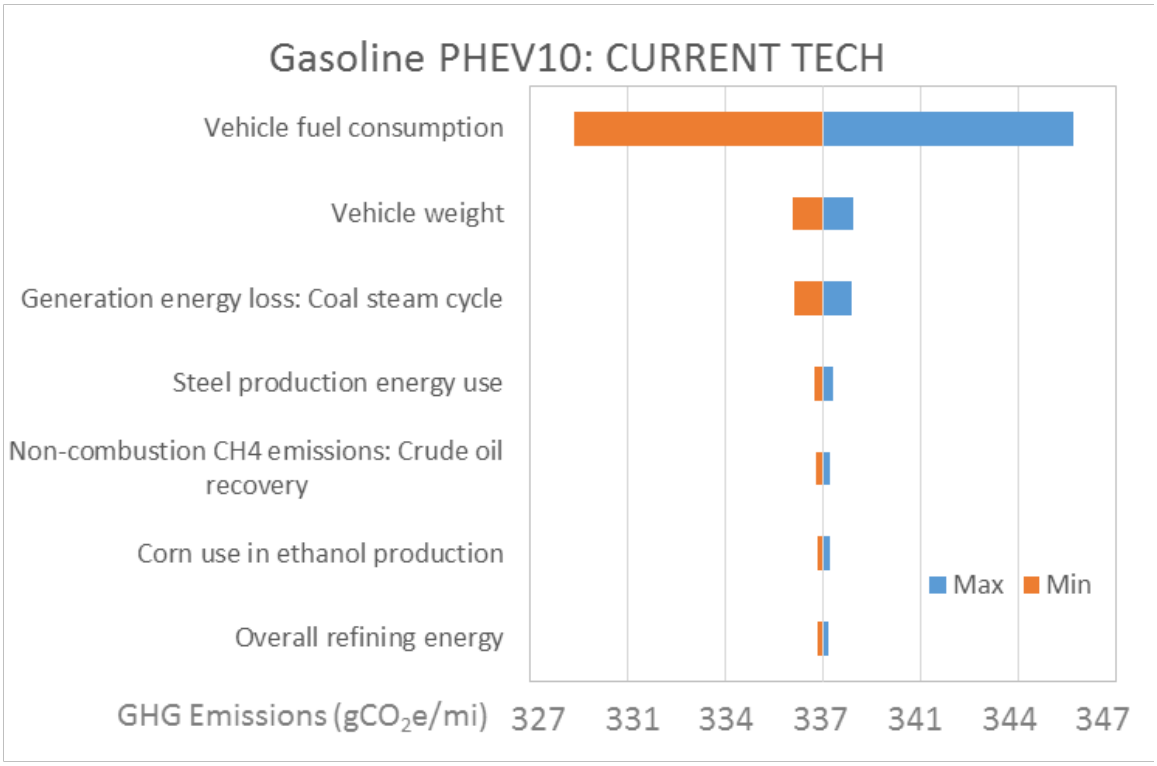

Figure D.8. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY PHEV10

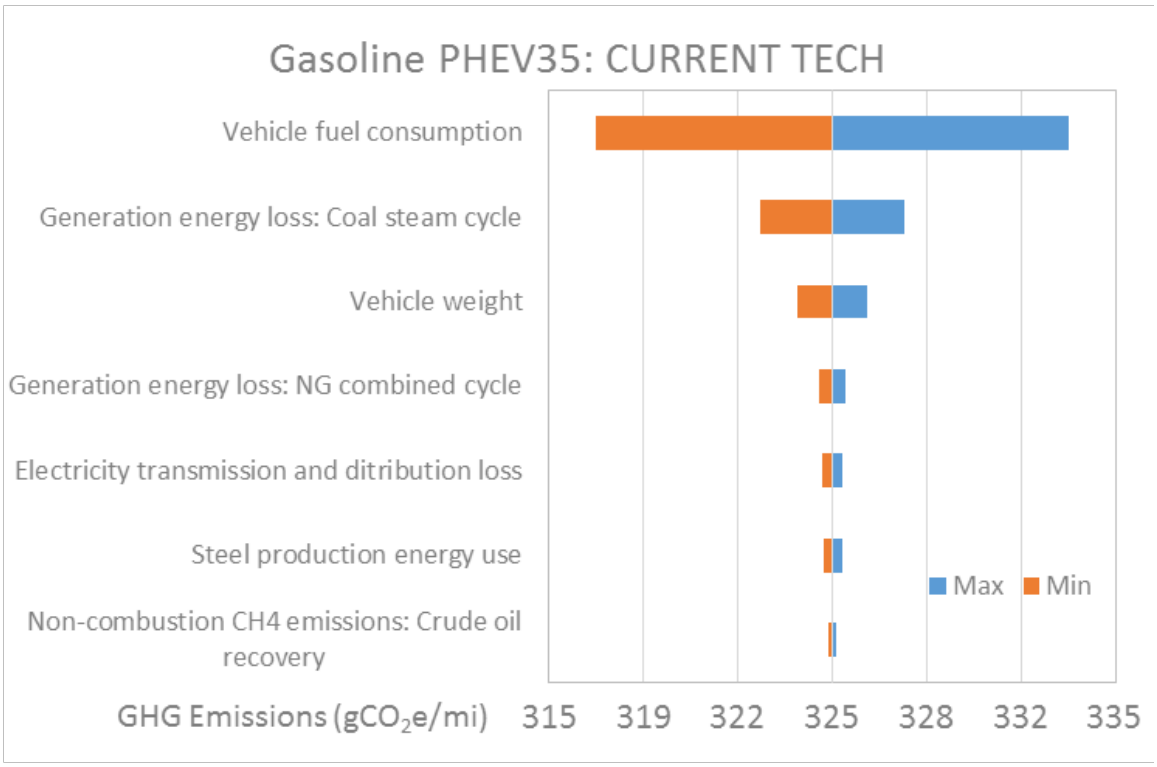

Figure D.9. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY PHEV35

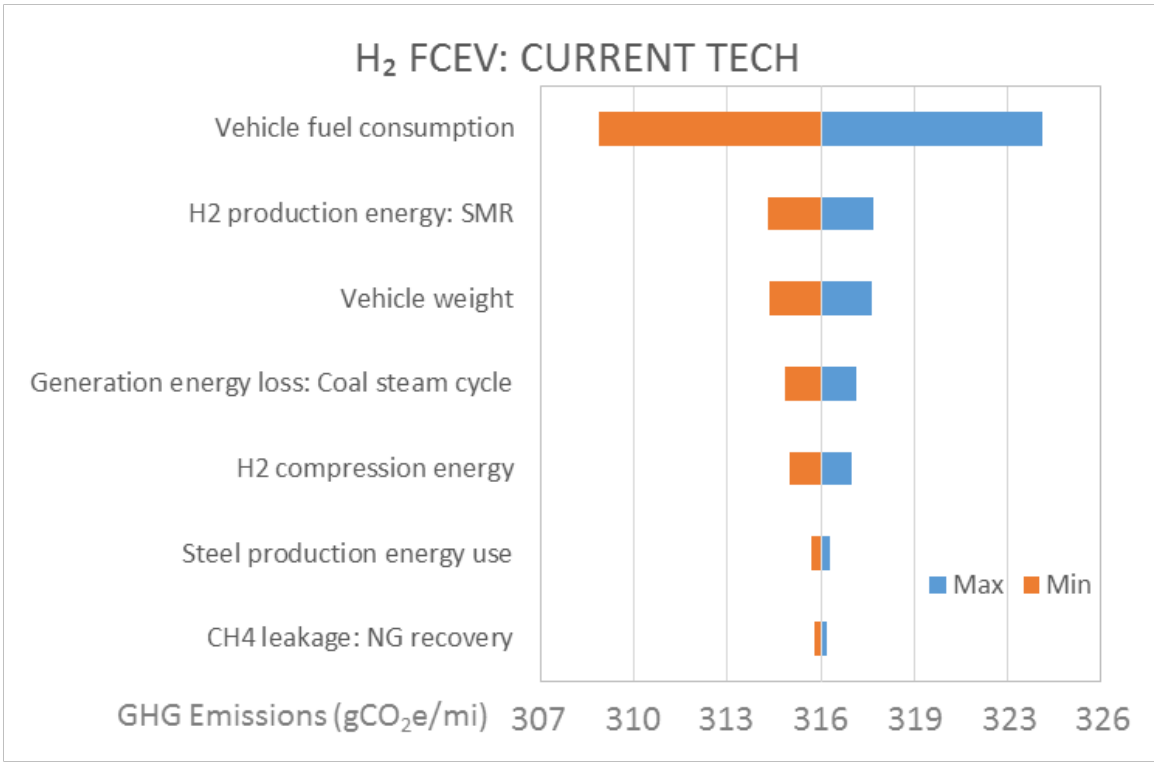

Figure D.10. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY H_2 FCEV

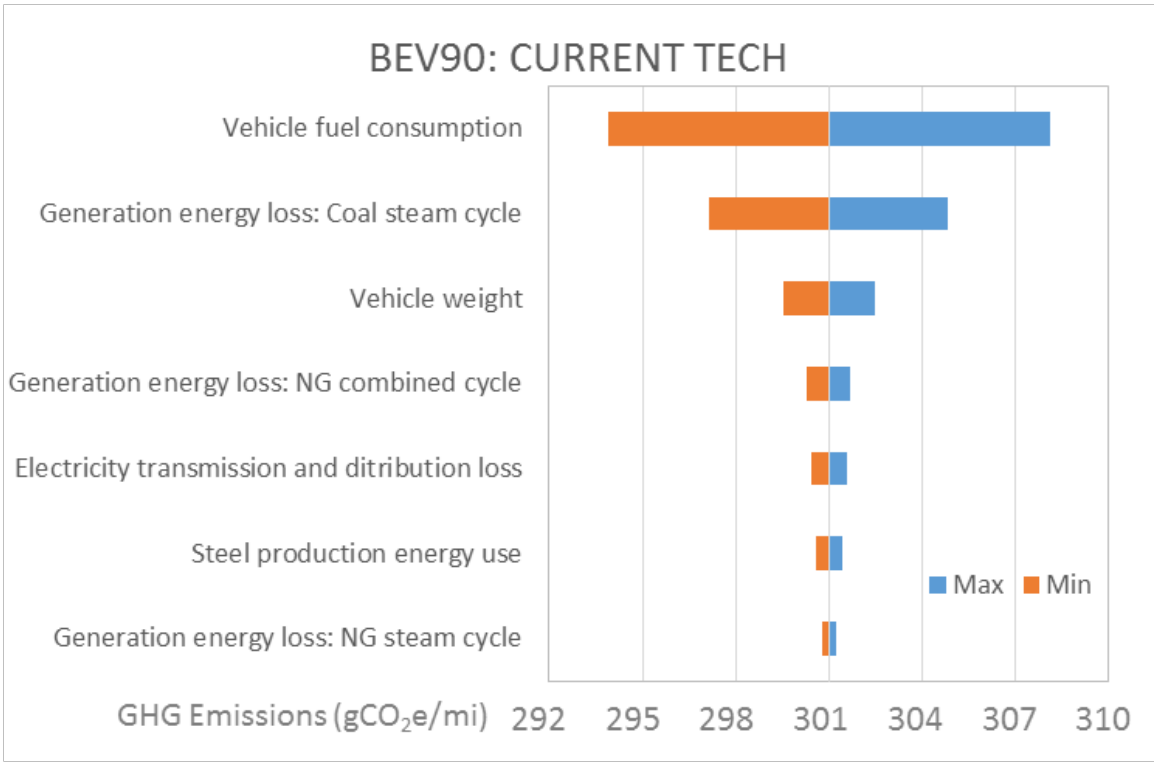

Figure D.11. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY BEV90

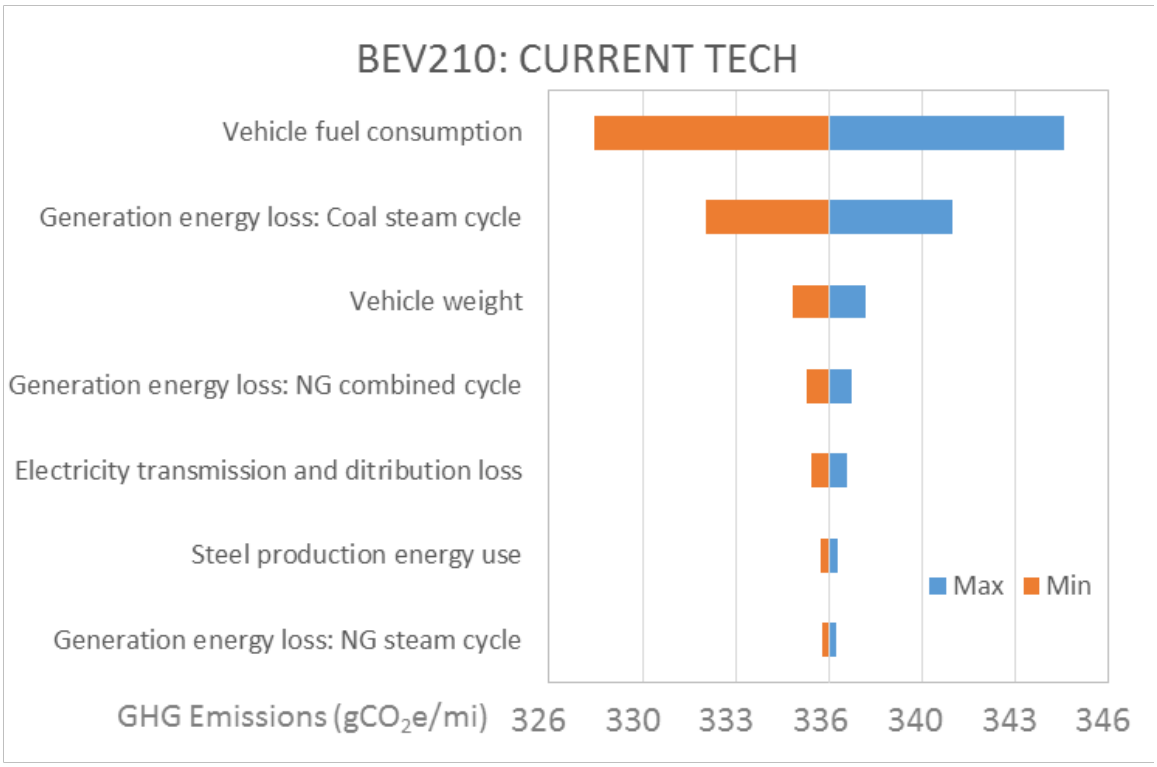

Figure D.12. Changes in GHG emissions for a 3% perturbation in each key parameter for CURRENT TECHNOLOGY BEV210

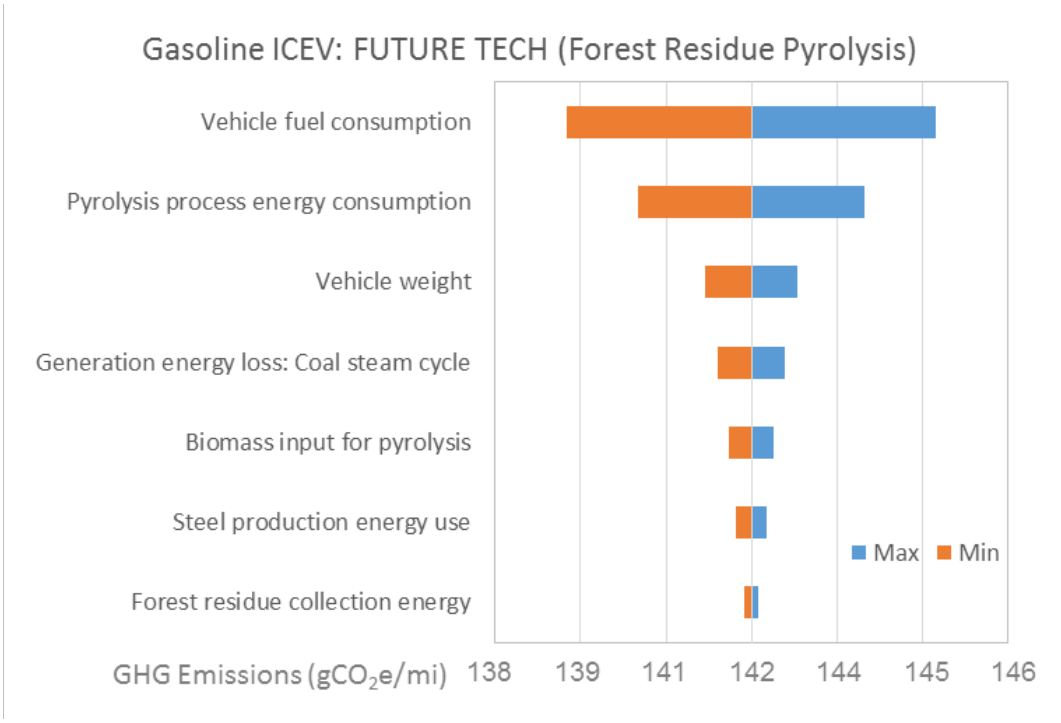

Figure D.13. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline ICEV – forest residue pyrolysis gasoline

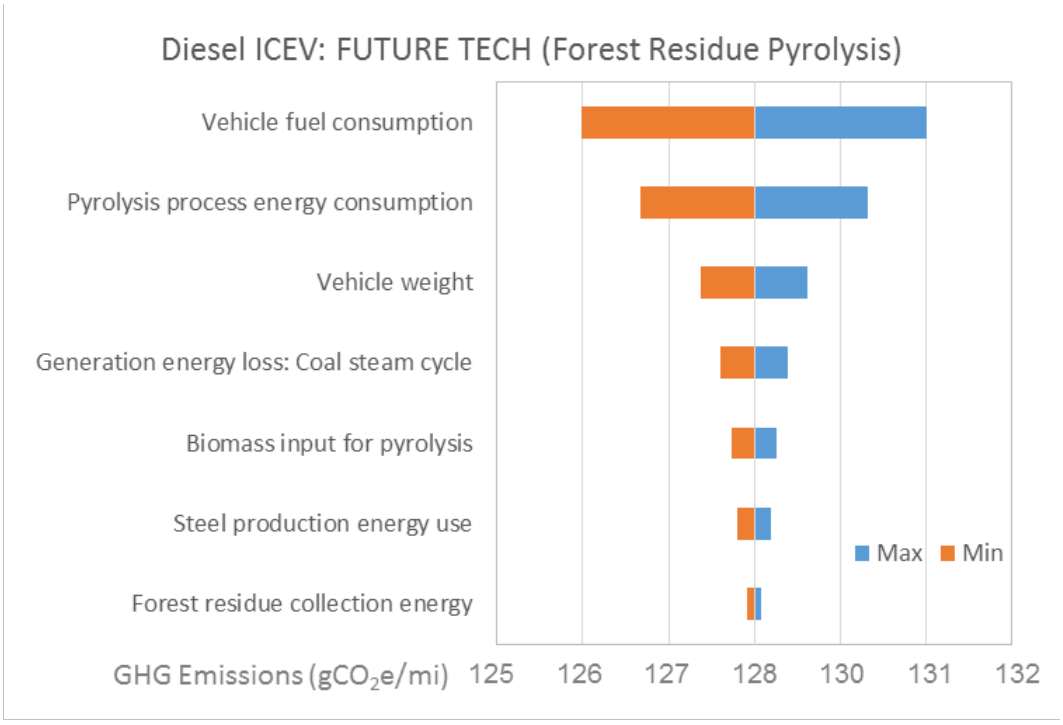

Figure D.14. Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – forest residue pyrolysis diesel

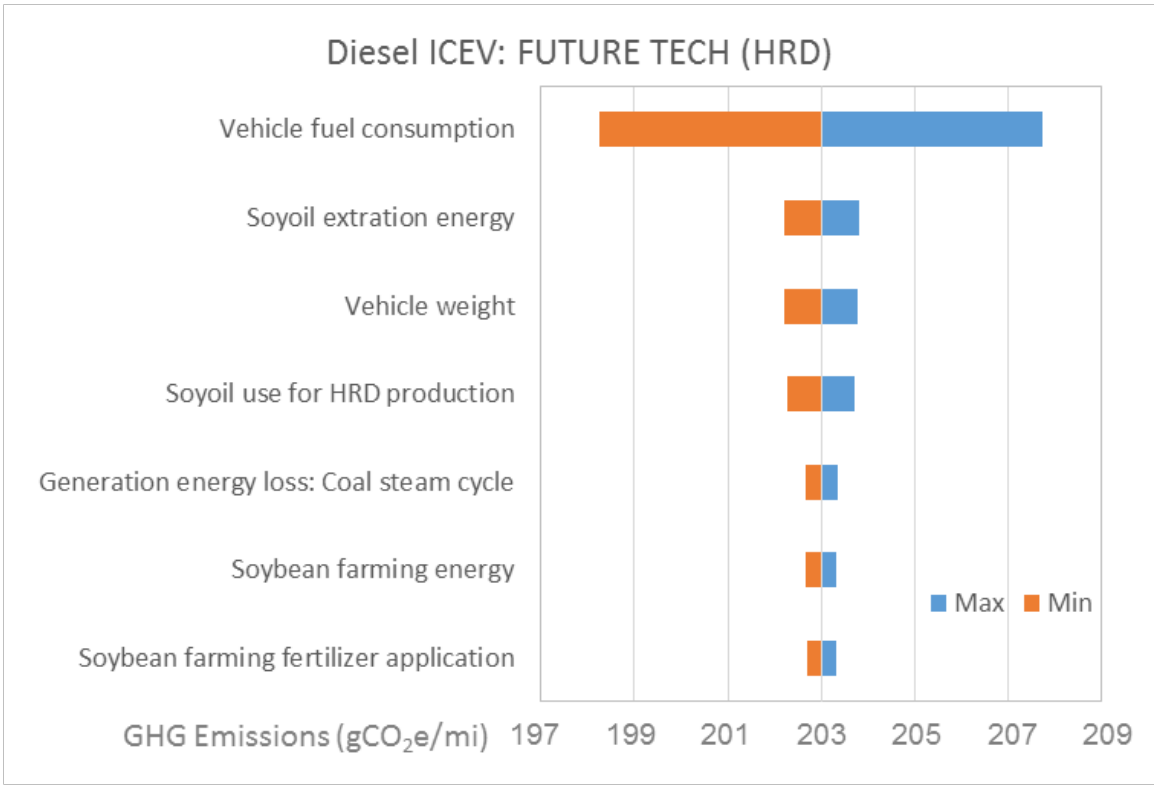

Figure D.15. Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – soybean-based HRD

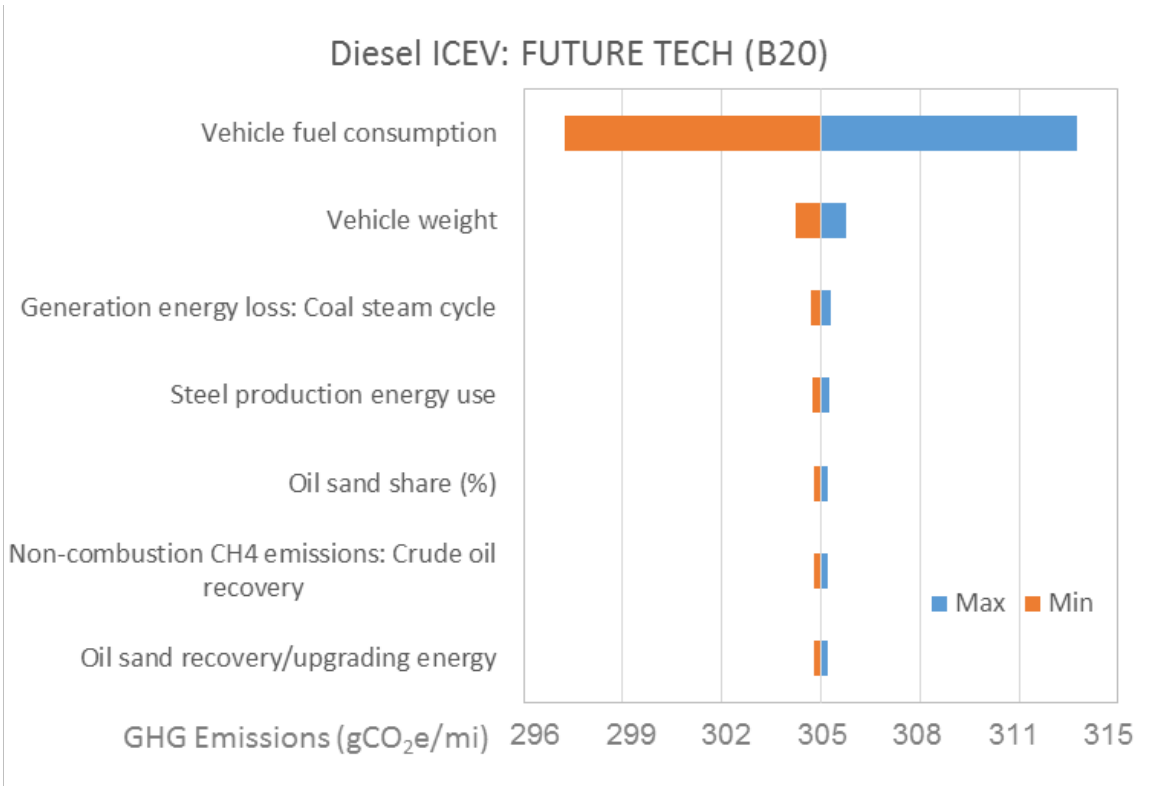

Figure D.16. Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – soybean-based B20

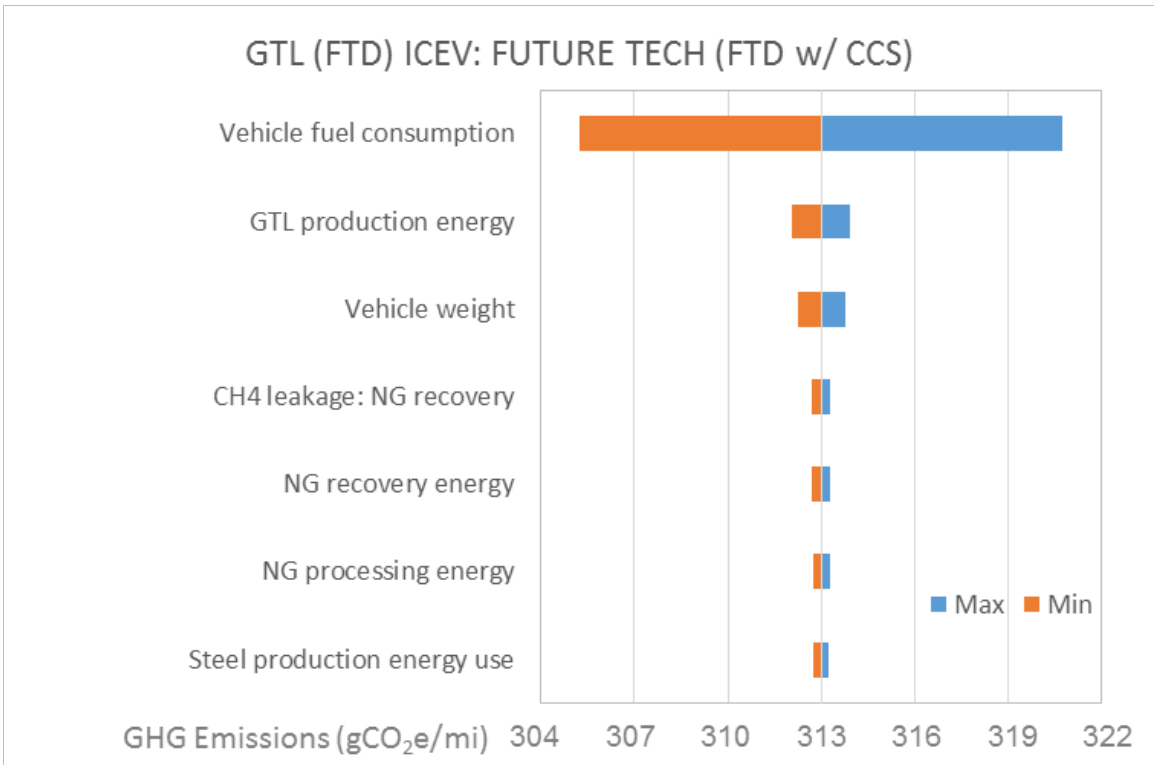

Figure D.17. Changes in GHG emissions for FUTURE TECHNOLOGY diesel ICEV – FTD with CCS

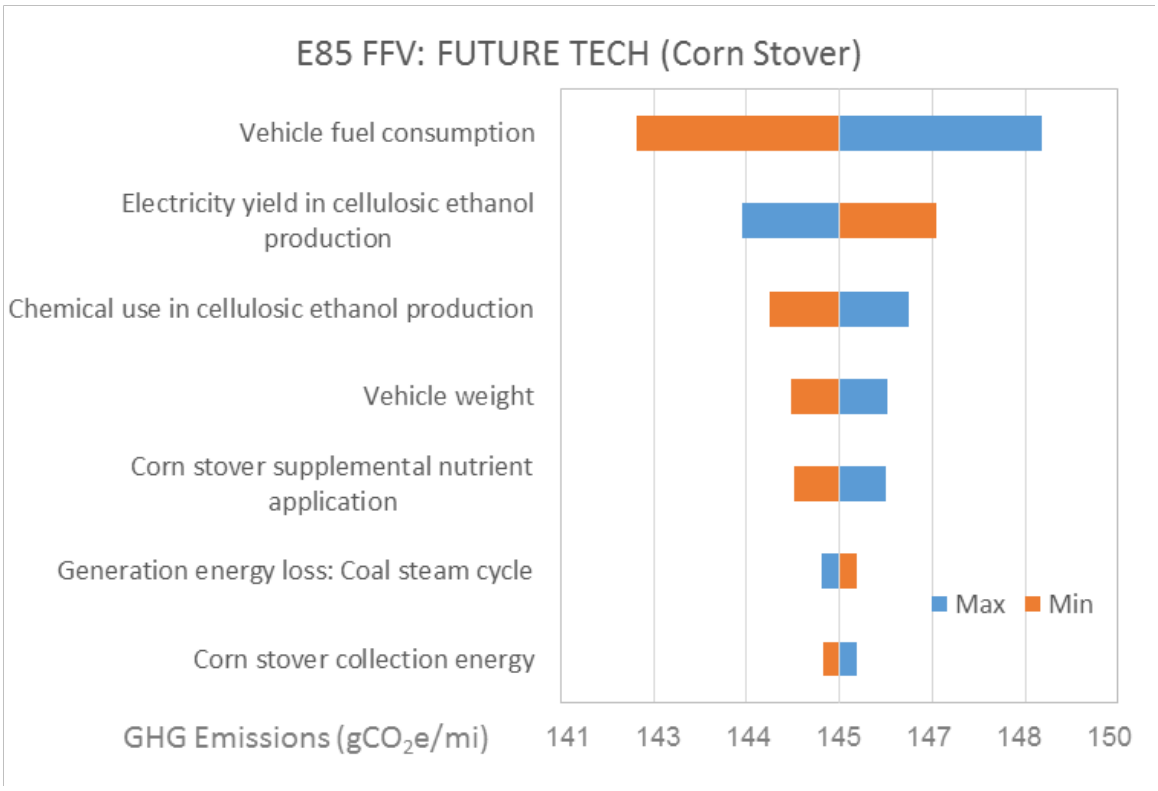

Figure D.18. Changes in GHG emissions for FUTURE TECHNOLOGY E85 FFV – corn stover-based ethanol

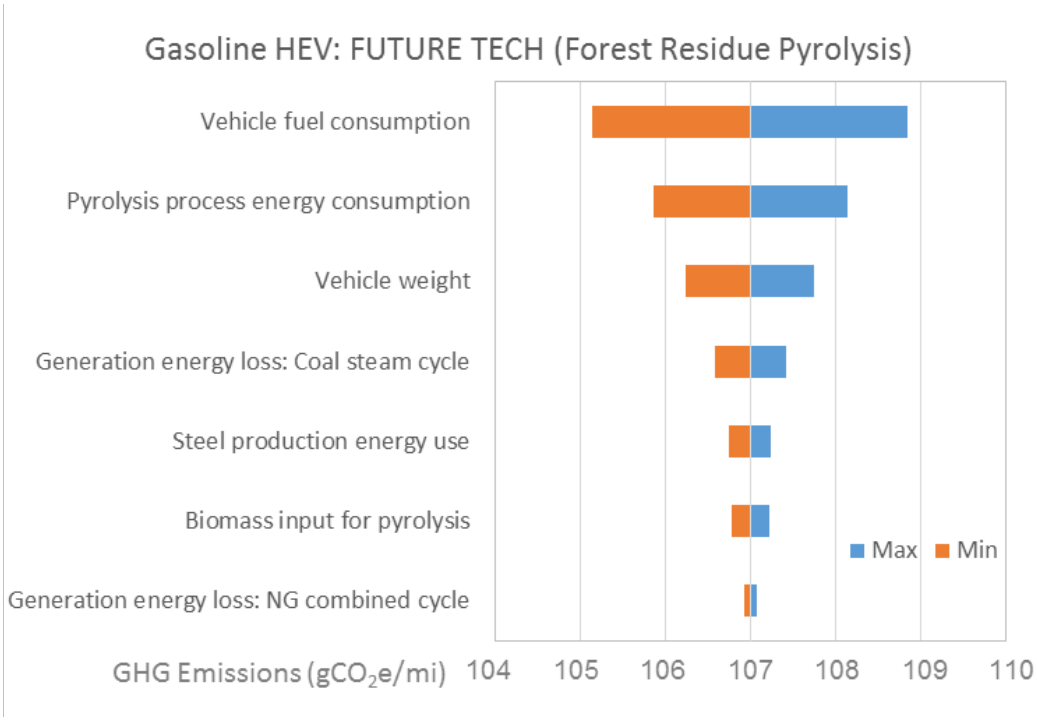

Figure D.19. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline HEV – forest residue pyrolysis gasoline

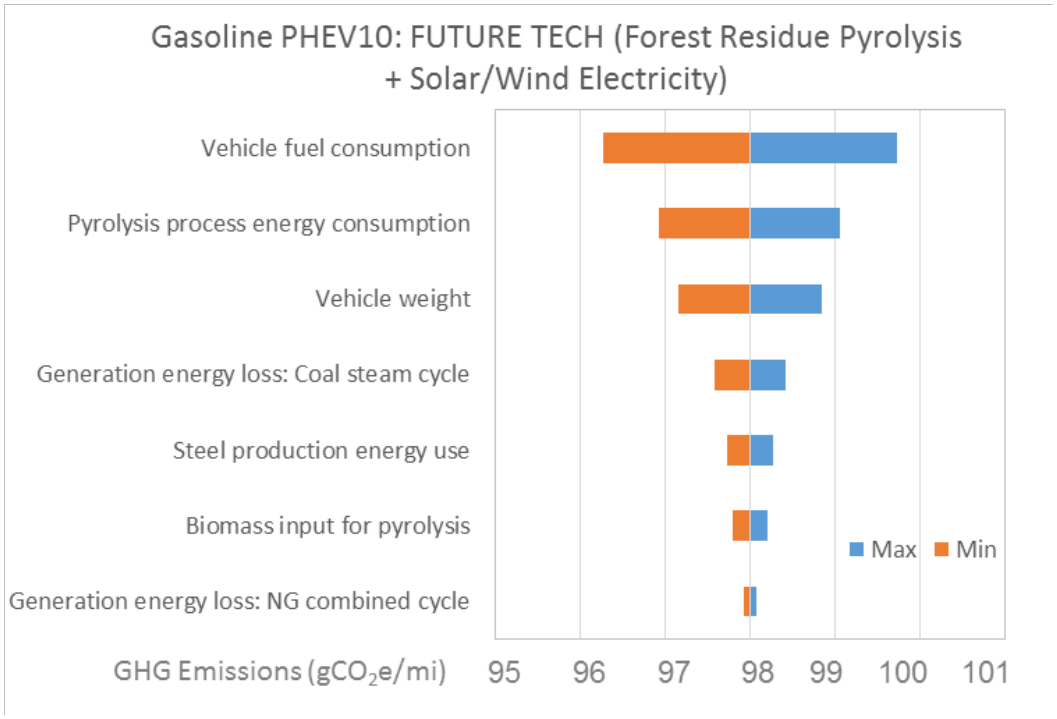

Figure D.20. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV10 – forest residue pyrolysis gasoline + solar/wind electricity

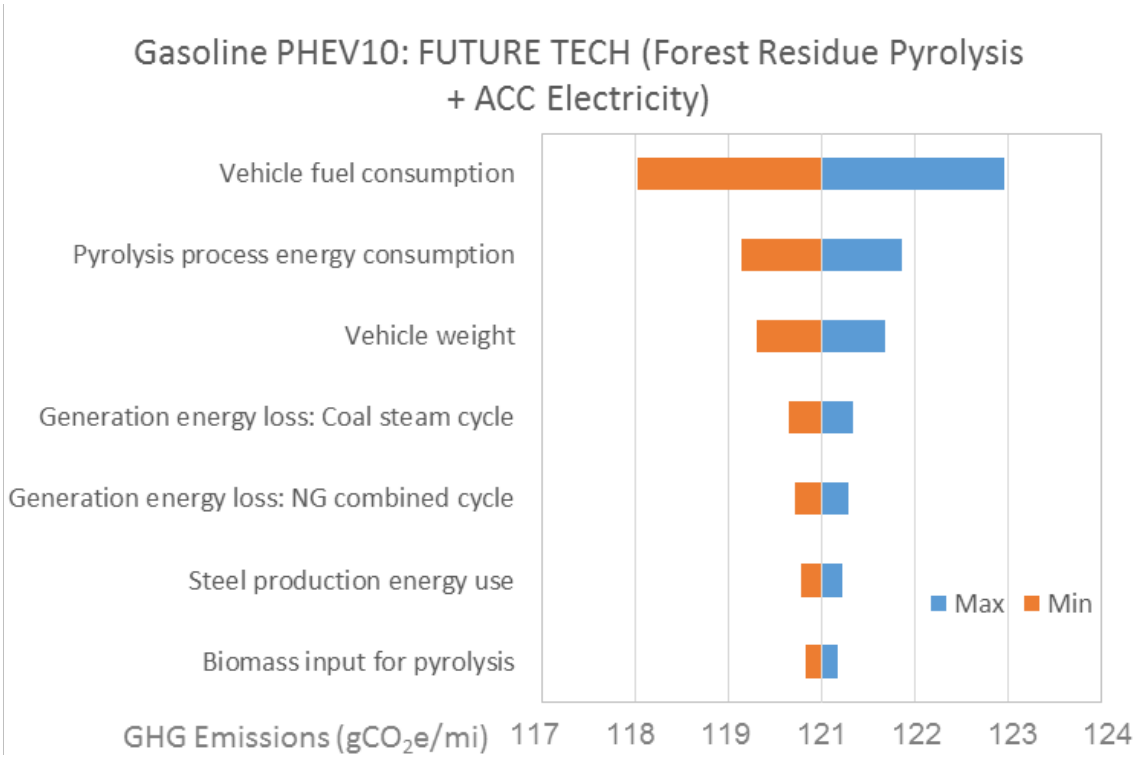

Figure D.21. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV10 – forest residue pyrolysis gasoline + ACC electricity

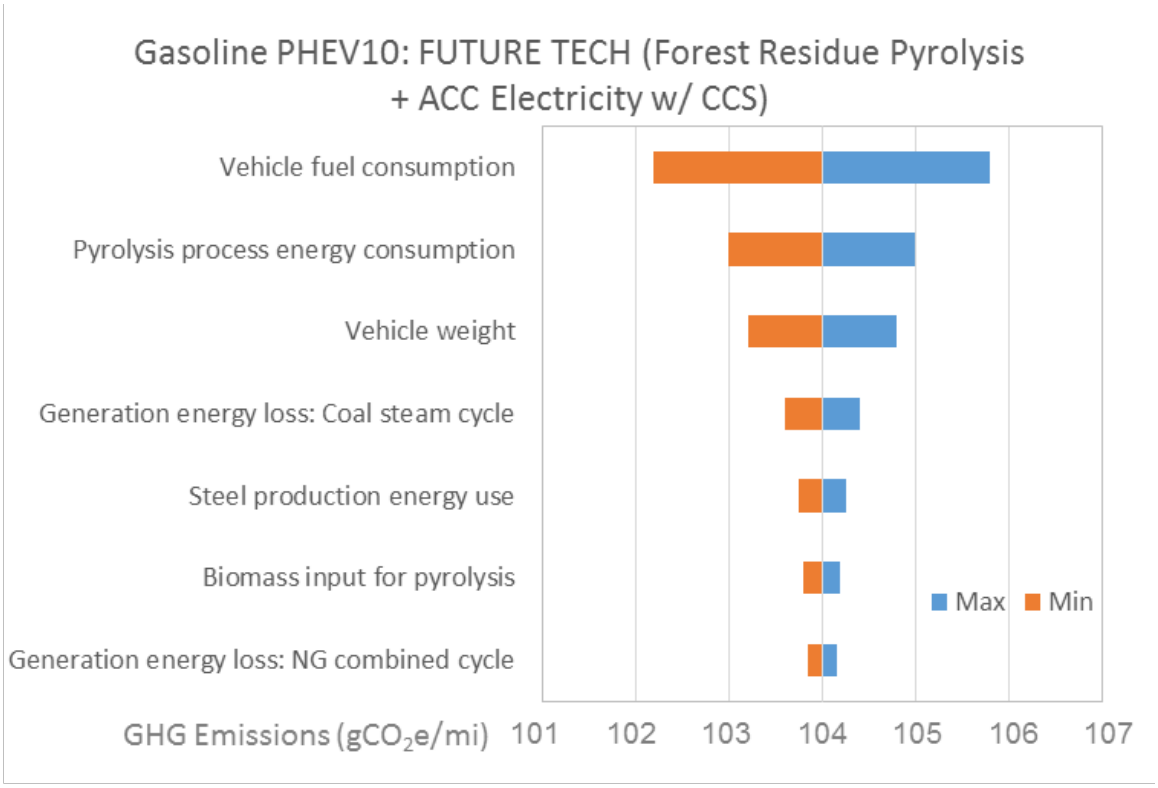

Figure D.22. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV10 – forest residue pyrolysis gasoline + ACC electricity with CCS

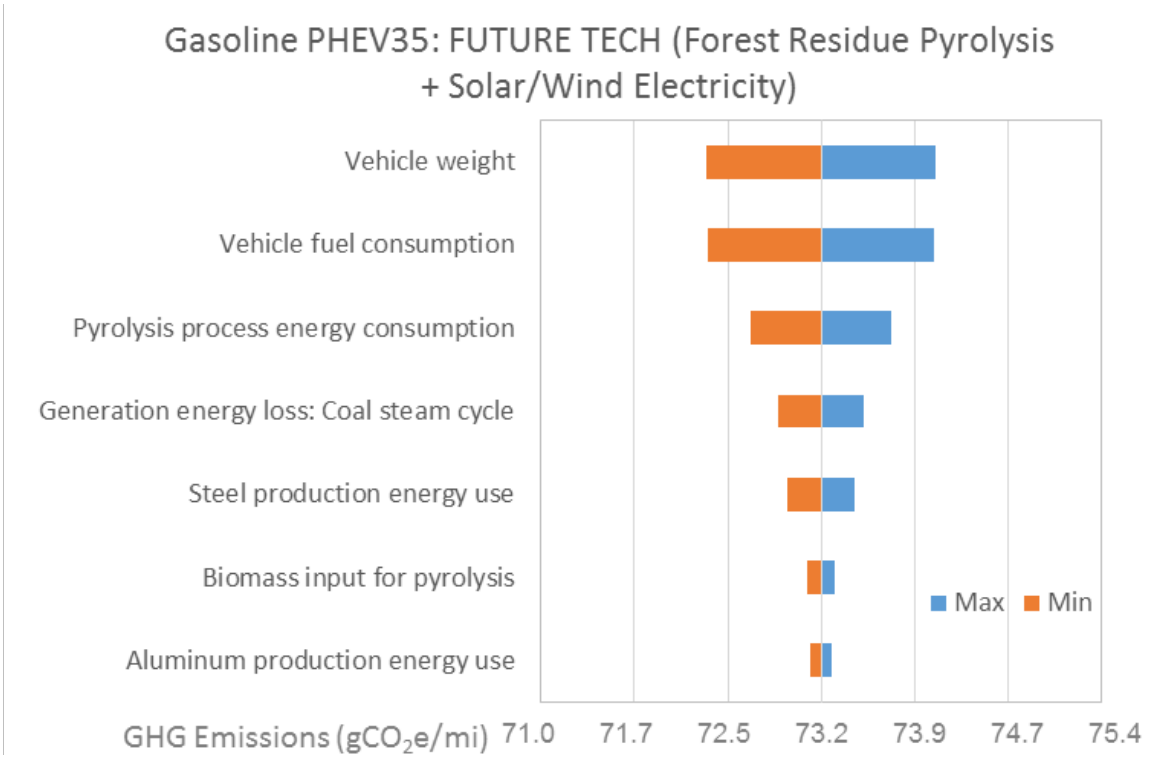

Figure D.23. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV35 – forest residue pyrolysis gasoline + solar/wind electricity

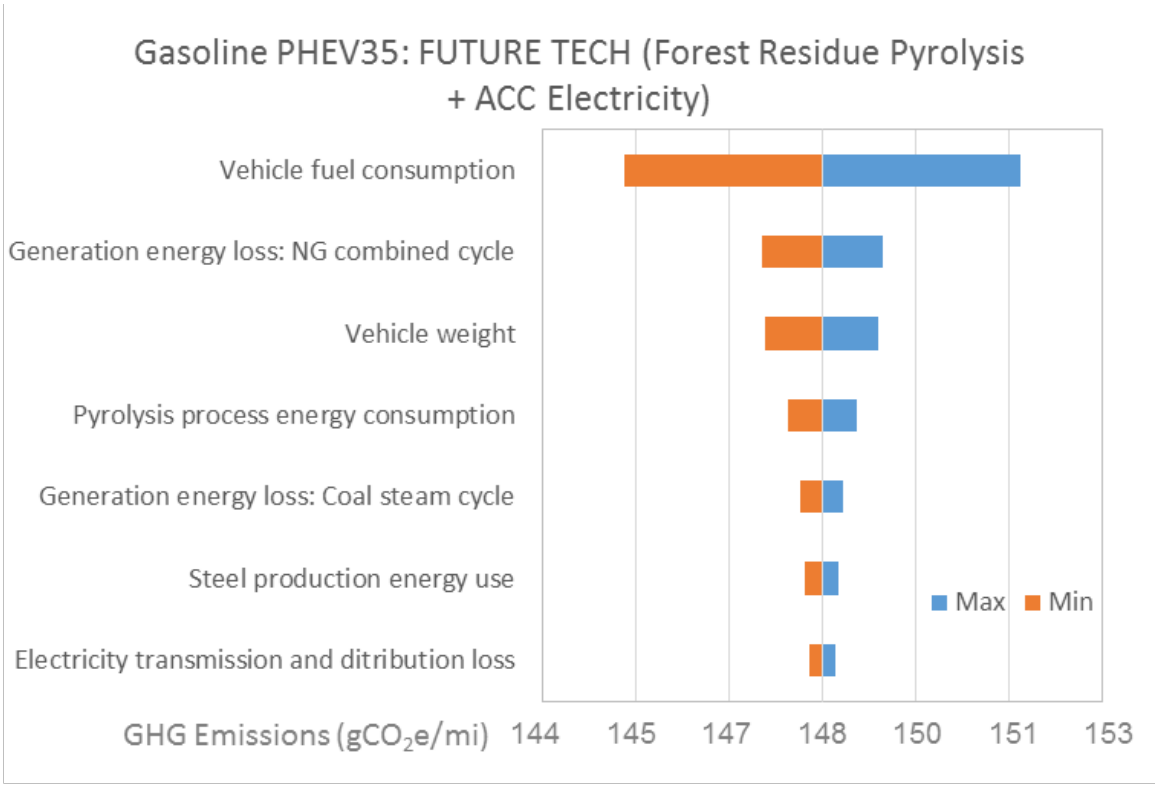

Figure D.24. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV35 – forest residue pyrolysis gasoline + ACC electricity

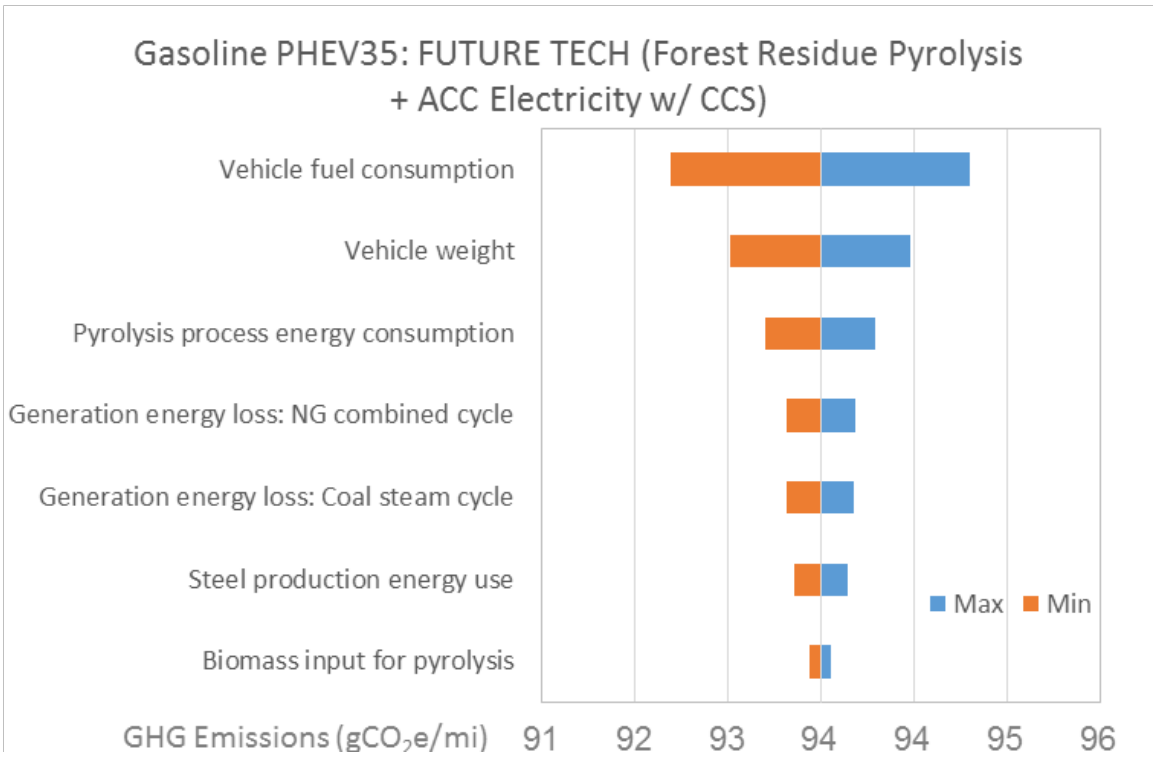

Figure D.25. Changes in GHG emissions for FUTURE TECHNOLOGY gasoline PHEV35 – forest residue pyrolysis gasoline + ACC electricity with CCS

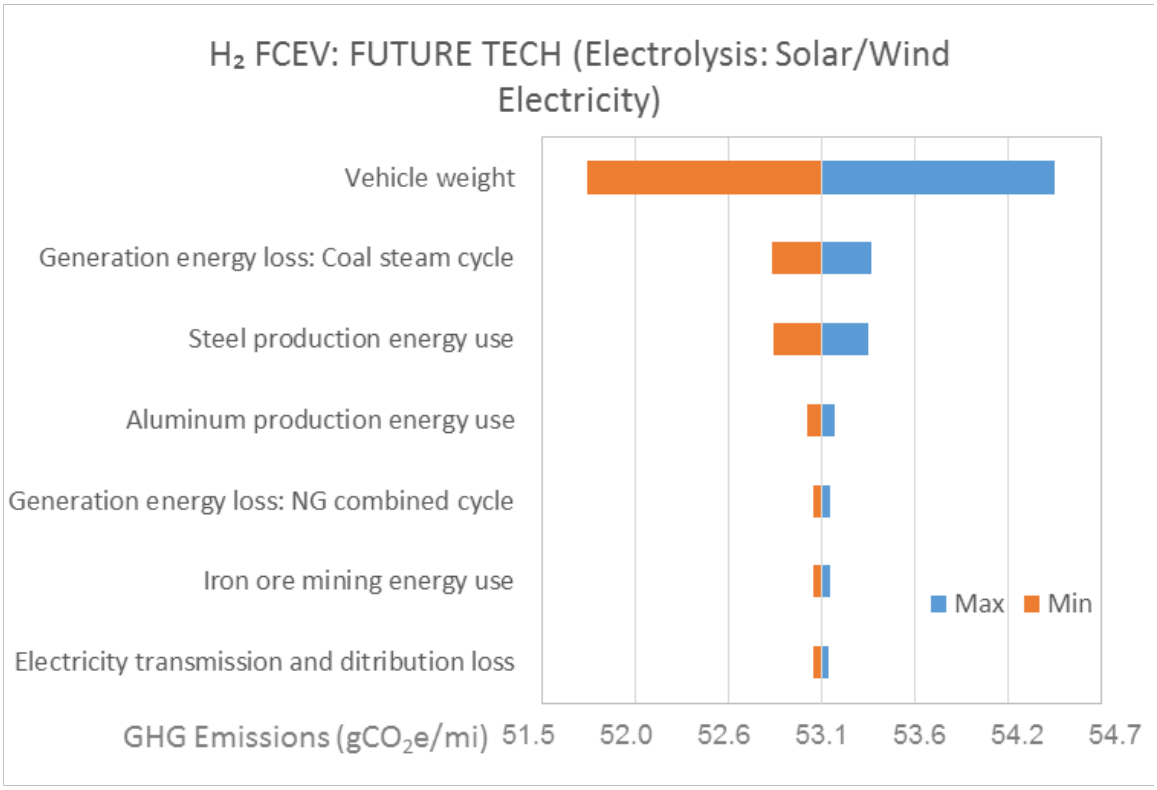

Figure D.26. Changes in GHG emissions for FUTURE TECHNOLOGY H_2 FCEV – electrolysis with solar/wind electricity

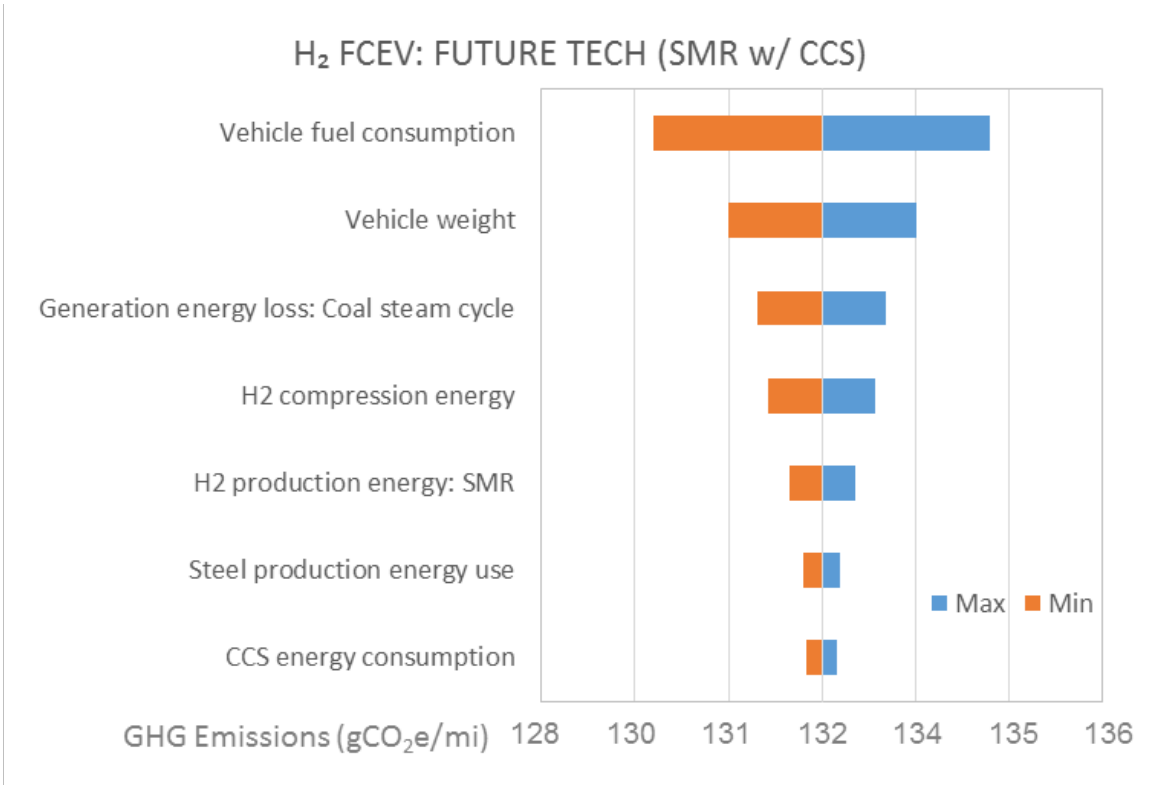

Figure D.27. Changes in GHG emissions for FUTURE TECHNOLOGY H_2 FCEV – NG SMR with CCS

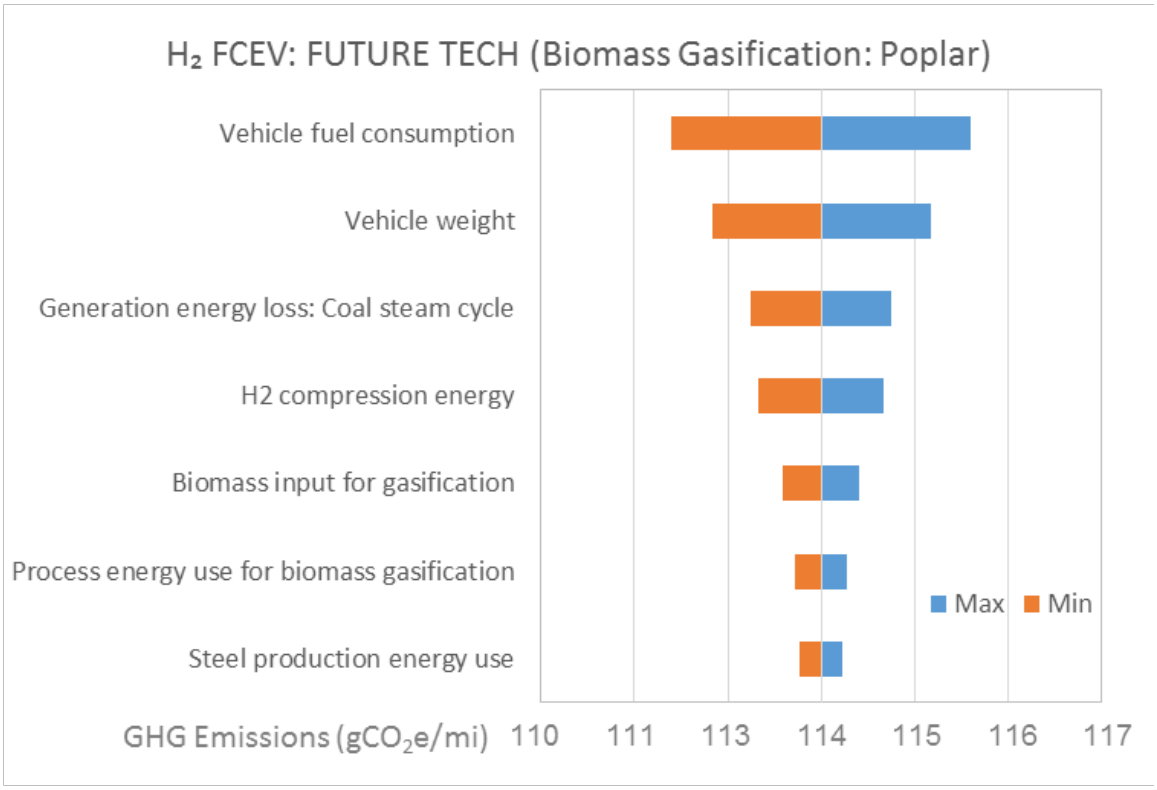

Figure D.28. Changes in GHG emissions for FUTURE TECHNOLOGY H_2 FCEV – biomass gasification using poplar

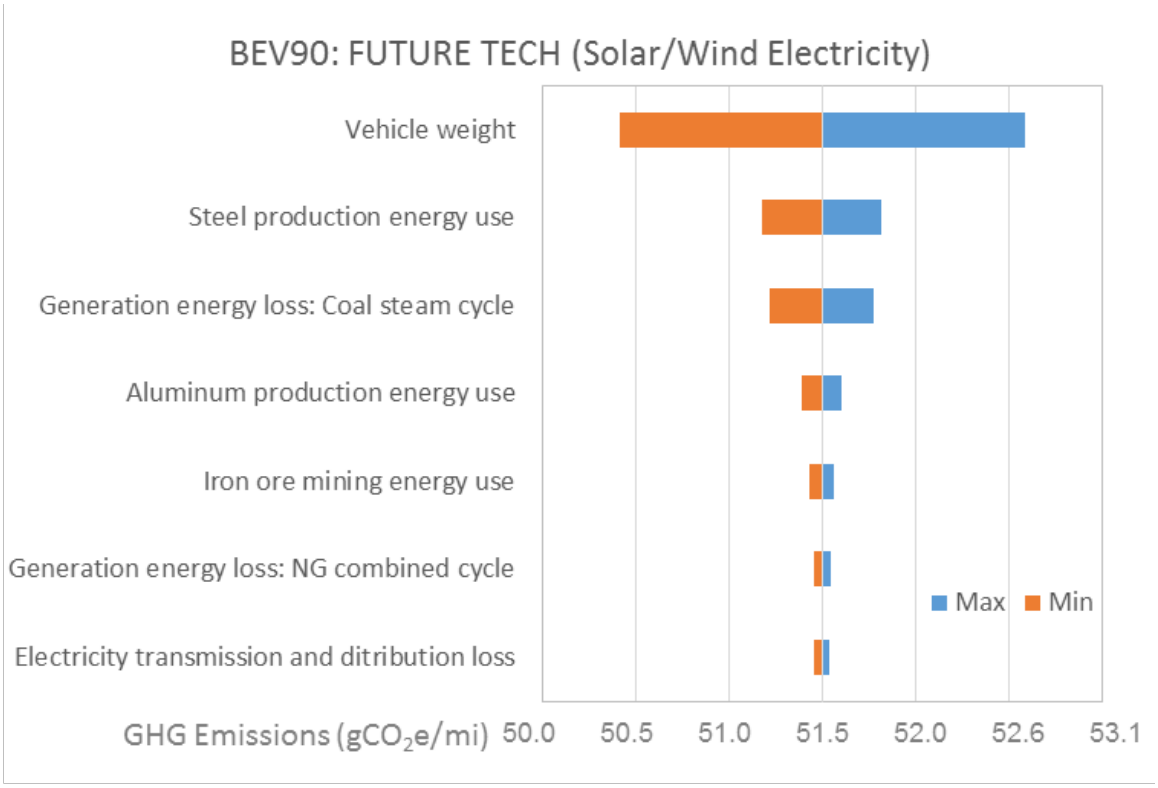

Figure D.29. Changes in GHG emissions for FUTURE TECHNOLOGY BEV90 – solar/wind electricity

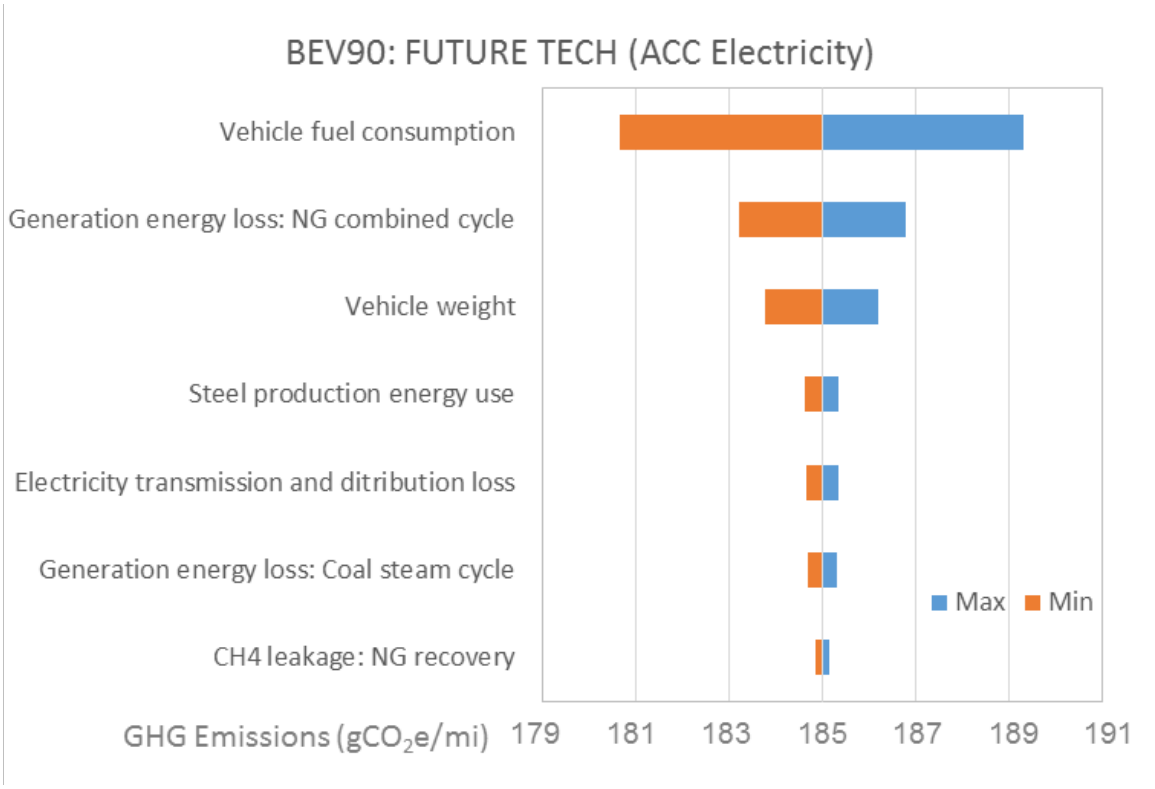

Figure D.30. Changes in GHG emissions for FUTURE TECHNOLOGY BEV90 – ACC electricity

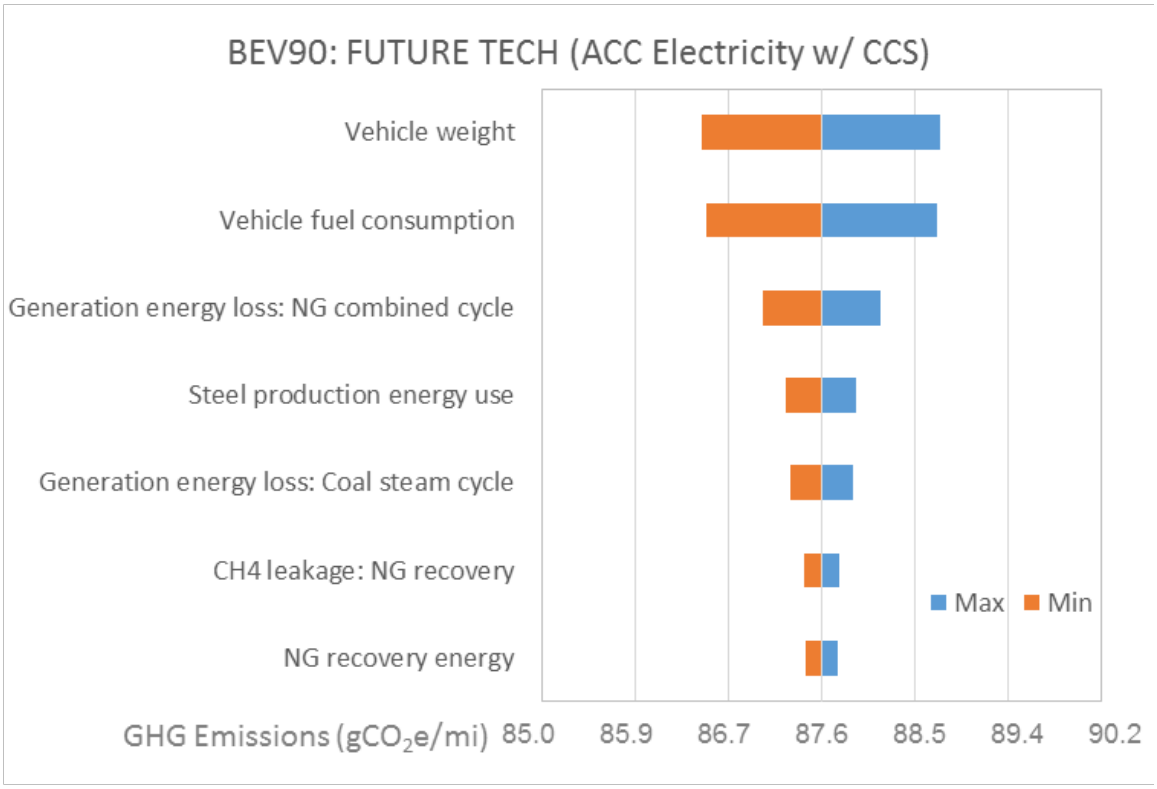

Figure D.31. Changes in GHG emissions for FUTURE TECHNOLOGY BEV90 – ACC electricity with CCS

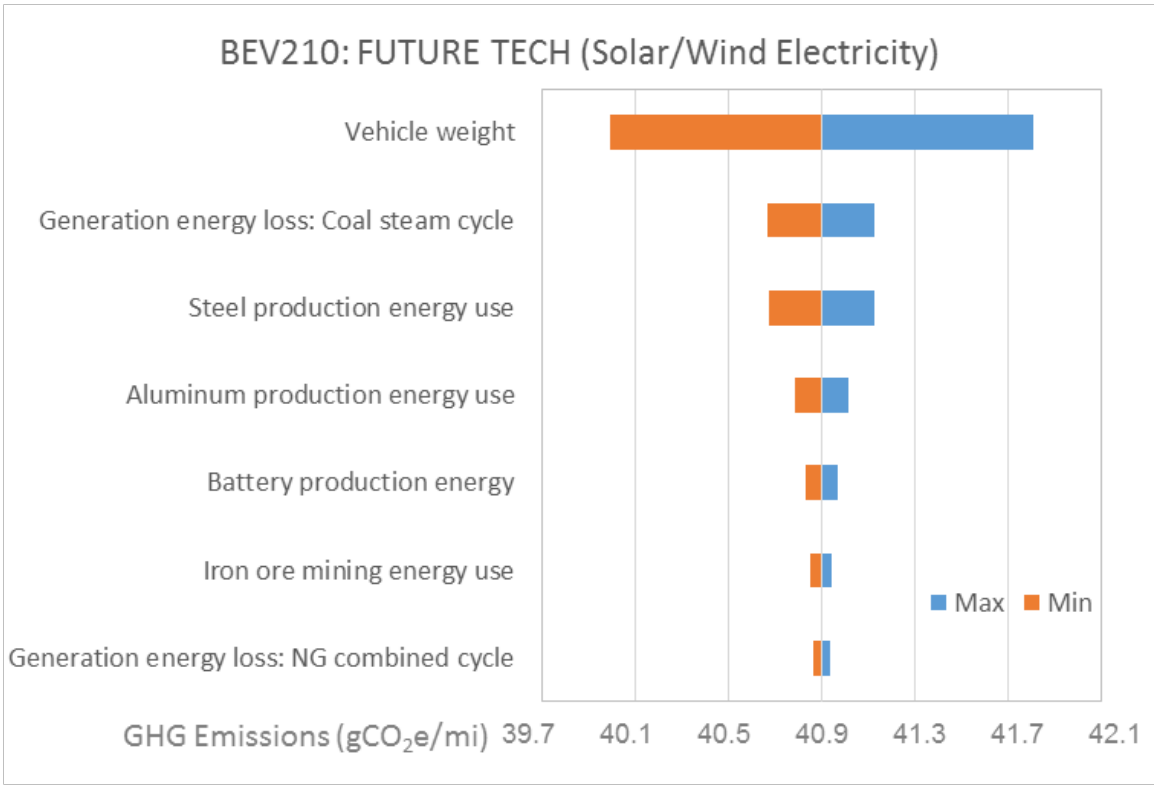

Figure D.32. Changes in GHG emissions for FUTURE TECHNOLOGY BEV210 – solar/wind electricity

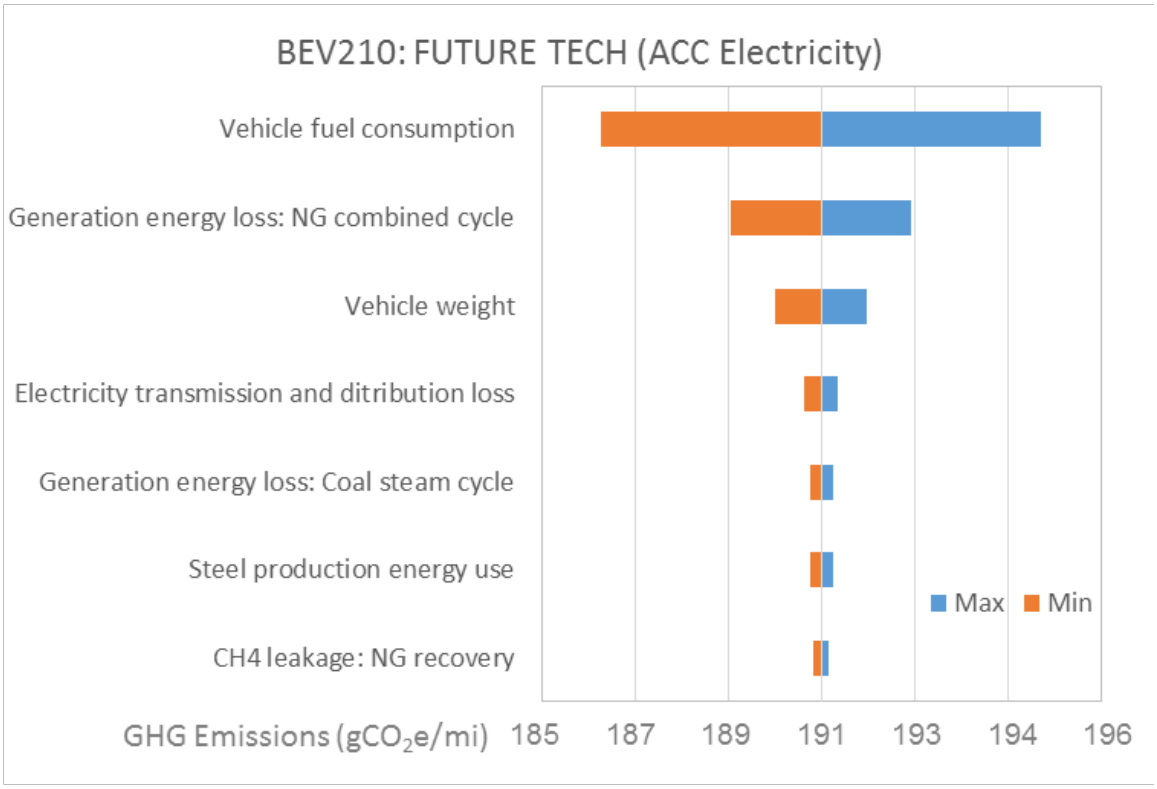

Figure D.33. Changes in GHG emissions for FUTURE TECHNOLOGY BEV210 – ACC electricity

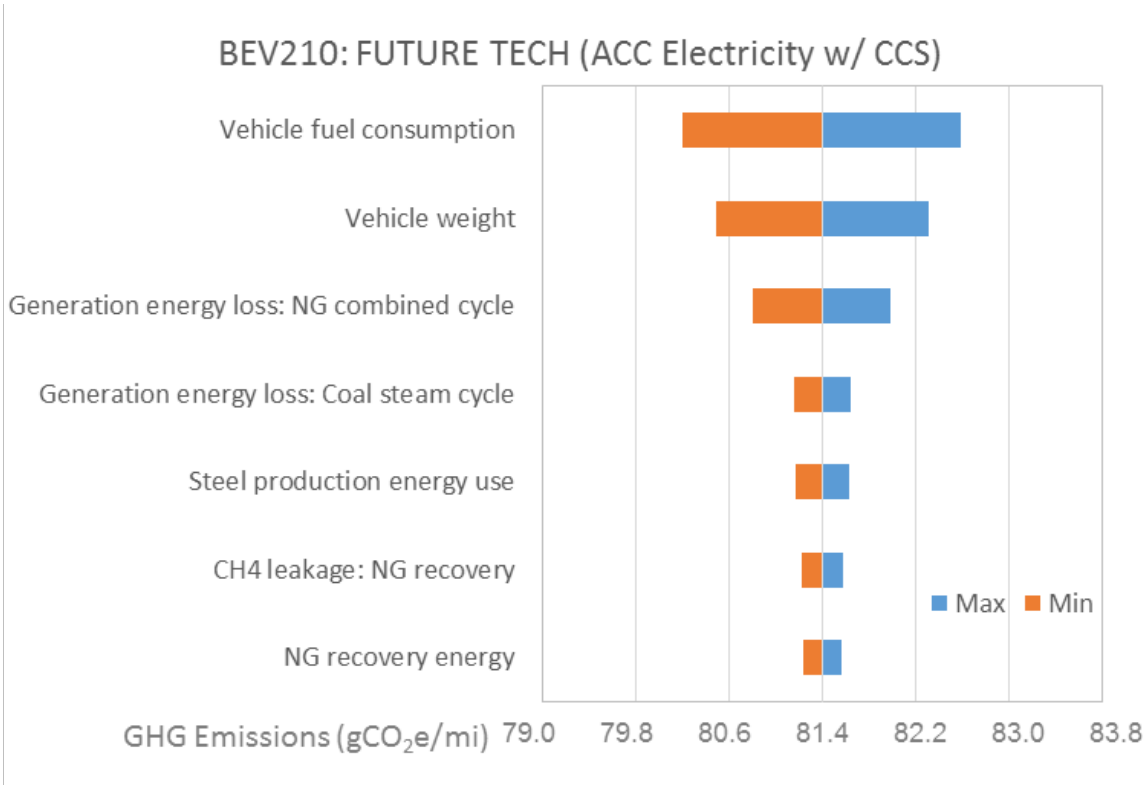

Figure D.34. Changes in GHG emissions for FUTURE TECHNOLOGY BEV210 – ACC electricity with CCS

Appendix E: LCD CALCULATION DETAILS AND EXAMPLES

This appendix provides more detail on the LCD calculations described in Section 9. LCD is defined as the sum of the amortized net vehicle cost per mile (LCD_{veh}) and the fuel cost component (LCD_{fuel}): $LCD = LCD_{veh} + LCD_{fuel}$. LCD has units of dollars per mile driven. The LCD calculation does not consider ownership costs other than vehicle or fuel (e.g., insurance, maintenance).

The LCD is a function of vehicle purchase cost, assumed vehicle residual value at the end of the analysis period, assumed discount rate, fuel costs, fuel efficiency, and assumed VMT. Costs in this study are considered in real dollars (2013$) not nominal dollars, and thus any assumed future inflation rate has been factored out of the analysis. Fuel costs are discussed in Section 5 and are assumed to remain constant in real dollar terms from the time of vehicle purchase through the end of the analysis period. As fuel costs are assumed to remain constant in real dollar terms, the fuel cost component of LCD can be calculated directly as the fuel cost (in 2013$/gge) divided by the vehicle fuel economy (in mpgge). The assumed discount rate plays no role in this calculation.

The vehicle cost component of the LCD is derived from the net vehicle cost to the owner, which is defined as the initial purchase cost of the vehicle (Section 6) less the residual value at the end of the analysis period. As discussed in Section 9, the analysis assumes that a vehicle depreciates in value by 17.5% each year on a nominal basis (82.5% of vehicle value is retained at the end of each year). Since the residual value is returned to the vehicle buyer after a number of years, it must be discounted to place it on a comparable basis with the initial vehicle purchase cost that occurs up front. Once it is discounted using the assumed discount rate, it may then be subtracted from the initial vehicle purchase cost to arrive at a net vehicle cost. The analysis uses a 5% discount rate as a base case, and considers sensitivity cases using 3% and 7% discount rates.

The vehicle cost component of the LCD is computed by allocating the net vehicle cost uniformly over the VMT, applying the assumed discount rate to reflect the years in which miles are driven. More specifically, the vehicle cost component of the LCD was found by solving the following equation:

$$Vehicle\ Cost\ (net) = \sum_{i=1}^{t} \frac{LCD_{veh} * VMT_i}{(1+D)^i} \tag{5}$$

where LCD_{veh} represents the vehicle cost component of the LCD metric (expressed in $/mile driven), t is the analysis time period in years, VMT_i is the number of miles driven in year i, D is the discount rate expressed as an annual percentage, and $(1 + D)^i$ is the discount factor applied in year i.

Table E.1 shows data and example calculations for the fuel cost component and the net vehicle cost for a 3-year analysis of the CURRENT TECHNOLOGY, HIGH VOLUME case gasoline ICEV pathway and for a 15-year analysis of the FUTURE TECHNOLOGY, HIGH VOLUME case gasoline ICEV pathway (all costs are in 2013$). Calculations for end-of-analysis-period residual value and the net present value (NPV) of that residual value are shown ("present" = time of vehicle purchase at beginning of the analysis period). Note that the analysis assumes a 15-year vehicle lifetime, and thus the residual value at the end of 15 years is assumed to be $0.

Table E.1. Sample calculations for the LCD fuel-cost component and net vehicle cost

Base Case (5% discount rate, mid-point vehicle and fuel cost)		**A**	**B**	**C**	**D**	**E**	**F**	**G**
Analysis Period	**Vehicle-Fuel Pathway**	**Fuel Cost ($/gge)**	**Vehicle FE (mpgge)**	**Fuel Cost Comp. ($/mi)**	**Vehicle Cost($)**	**Residual Value (nominal) ($/mi)**	**Residual Value (NPV) ($/mi)**	**Net Vehicle Cost($)**
3-year case	Gasoline ICEV (CURRENT TECHNOLOGY, HIGH VOLUME)	1.80	26.2		21,384			
	Calculation			A/B		D×0.825^3	E/(1.05)^3	D - F
	Calculation results			0.07		12,008	10,373	11,102
15-year case	Gasoline ICEV (FUTURE TECHNOLOGY, HIGH VOLUME)	2.44	34.5		23,491			
	Calculation			A/B		0 (assumed)	0	D - 0
	Calculation results			0.07		0	0	23,491

As can be seen in Table E.1, the calculation of the total net vehicle cost (purchase cost less residual value) is a straight-forward NPV calculation. Calculation of the vehicle cost component of the LCD from this net vehicle cost is more complicated, particularly as the mileage schedule assumed in the analysis is not constant over time. As noted, calculation of the vehicle cost component is done by solving the Equation (5) for a constant per-mile value. This amortizes the net vehicle cost uniformly over all miles driven during the analysis period.

Detailed calculations to solve for the vehicle cost component are not shown in this appendix. Table E.2, however, shows CURRENT TECHNOLOGY, HIGH VOLUME case and FUTURE TECHNOLOGY, HIGH VOLUME case example results for a gasoline ICEV. The table shows the LCD_{veh} components derived from the example cases in Table E.1. The total annual vehicle cost allocations (on a nominal basis) can be easily calculated as the annual VMT times the LCD_{veh} cost component. These annual costs are then put into present value terms using the discount rate to demonstrate that their sum, when discounted back to a present value basis, does indeed equal the net cost of the vehicle.

Finally, Table E.3 shows the total LCD costs for the examples shown in this appendix, reflecting the fuel cost components shown in Table E.1 and the vehicle cost components shown in Table E.2. For the examples shown: (1) the 3-year CURRENT TECHNOLOGY, HIGH VOLUME case analysis of a gasoline ICEV has a total LCD of $0.36/mi and (2) the 15-year FUTURE TECHNOLOGY, HIGH VOLUME case analysis of a gasoline ICEV has a total LCD of $0.26/mi. These are the same total LCD costs for gasoline ICEVs shown in for the current and future cases in Tables 54 and 55, respectively, in Section 10.

Table E.2. Sample data for the LCD vehicle-cost component showing the annual vehicle costs on an NPV basis

Base Case (5% discount rate, mid-point vehicle and fuel cost)		**Net Vehicle Cost (from D-1) ($)**	**LCD_{veh} ($/mi)**	**Year**	**Annual Miles**	**Vehicle Cost (Annual) $LCD_{veh} \times VMT / (1+D)^{year}$ ($)**	**Vehicle Cost (Total) ($)**
Analysis Period	**Vehicle-Fuel Pathway**						
3-year case	Gasoline ICEV (CURRENT TECHNOLOGY, HIGH VOLUME)	11,102	0.29				
				1	14,231	3,925	
				2	13,961	3,667	
				3	13,669	3,420	
							11,102
15-year case	Gasoline ICEV (FUTURE TECHNOLOGY, HIGH VOLUME)	23,491	0.19				
				1	14,231	2,515	
				2	13,961	2,349	
				3	13,669	2,191	
				4	13,357	2,039	
				5	13,028	1,894	
				6	12,683	1,756	
				7	12,325	1,625	
				8	11,956	1,501	
				9	11,578	1,385	
				10	11,193	1,275	
				11	10,804	1,172	
				12	10,413	1,076	
				13	10,022	986	
				14	9,633	903	
				15	9,249	825	
							23,491

Table E.3. LCD cost components for two examples

Base Case (5% discount rate, mid-point vehicle and fuel cost)		**LCD Fuel Cost Component ($/mi)**	**LCD Vehicle Cost Component ($/mi)**	**LCD Total ($/mi)**
Analysis Period	**Vehicle-Fuel Pathway**			
3-year case	Gasoline ICEV (CURRENT TECHNOLOGY, HIGH VOLUME)	0.07	0.29	0.36
15-year case	Gasoline ICEV (FUTURE TECHNOLOGY, HIGH VOLUME)	0.07	0.19	0.26

Appendix F: COMPARISON BETWEEN FUEL PRICE PROJECTIONS

This appendix details the effect of fuel price volatility on the results for LCD and cost of avoided GHG emissions in this report. Crude oil prices fell in 2014 and 2015, resulting in lower price projections (EIA 2015a) relative to EIA (2014a). Here, LCD and cost of avoided GHGs were calculated using projected values for fuel prices from AEO 2014 to contrast with the values from AEO 2015 presented in the body of this report. Table F.1 shows the key differences between AEO 2014 and AEO 2015 as related to this report (see Table 31 for a list of all fuel cost assumptions). AEO 2014 price data are provided in 2012$, with fuel prices provided in $/MMBtu. These prices were converted to 2013$ using price deflator data (BEA 2015, Table 1.1.9), and highway fuel taxes were removed, as described in Section 5.2.

Table F.1. Key differences between AEO 2014 and AEO 2015 (2013$/gge unless noted)

Fuel type	AEO 2014 Projection		AEO 2015 Projection	
	CURRENT	FUTURE	CURRENT	FUTURE
Crude oil ($/barrel to refinery)	90	64/102/150	50	57/82/158
Gasoline	2.74	2.11/2.86/3.81	1.80	1.90/2.44/4.04
Petroleum diesel	2.69	2.23/3.07/4.14	1.90	2.01/2.60/4.40
FAME (B20)		2.30/3.11/4.16		2.12/2.72/4.37
CNG	1.91	1.84/1.90/2.35	2.04	1.95/2.02/2.51
LPG	2.38	2.46/2.68/2.93	2.17	2.26/2.49/2.98
E85	3.35		2.21	
Electricity (grid mix)	3.97		3.98	
Electricity (ACC w/ CCS)		4.99		5.43
Electricity (wind)		4.62		4.56
Hydrogen (NG SMR) (high/low volume)	5.24/9.44	4.78	4.90/9.10	4.59

By analyzing the LCD and cost of avoided GHG emissions for each price projection, we can examine the effect of a change in fuel prices. Vehicle price is the major component of the LCD when projected at volume, and fuel price is the minor component. Therefore, relatively small changes are seen for the LCD in both the CURRENT TECHNOLOGY case (as seen by comparing Figure F.1 to Figure 22) and the FUTURE TECHNOLOGY case (examined in Figure F.2, compared to Figure 23). (Figures from Section 10 are repeated in this appendix for the reader's convenience.)

The cost of avoided GHG emissions is relatively insensitive to changes in oil price. These results are shown in Figure F.3 (CURRENT TECHNOLOGY, HIGH VOLUME, compared to Figure 33) and Figure F.4 (FUTURE TECHNOLOGY, HIGH VOLUME, compared to Figure 34). In many cases, the cost of the alternative fuel is correlated with that of the gasoline reference, so changes in the cost of avoided GHG emissions for the alternative technology are muted. The largest change is in the cost of avoided GHG emissions for the CURRENT TECHNOLOGY, HIGH VOLUME LPG and CNG pathways, fuels that did not have the same magnitude of price change between AEO 2014 and AEO 2015 as petroleum did. For other CURRENT TECHNOLOGY, HIGH VOLUME vehicle-fuel pathways, the 15-year costs of avoided GHG emissions increase by up to approximately $200–$300/tonne CO_2e when analyzed using AEO 2014 instead of AEO 2015.

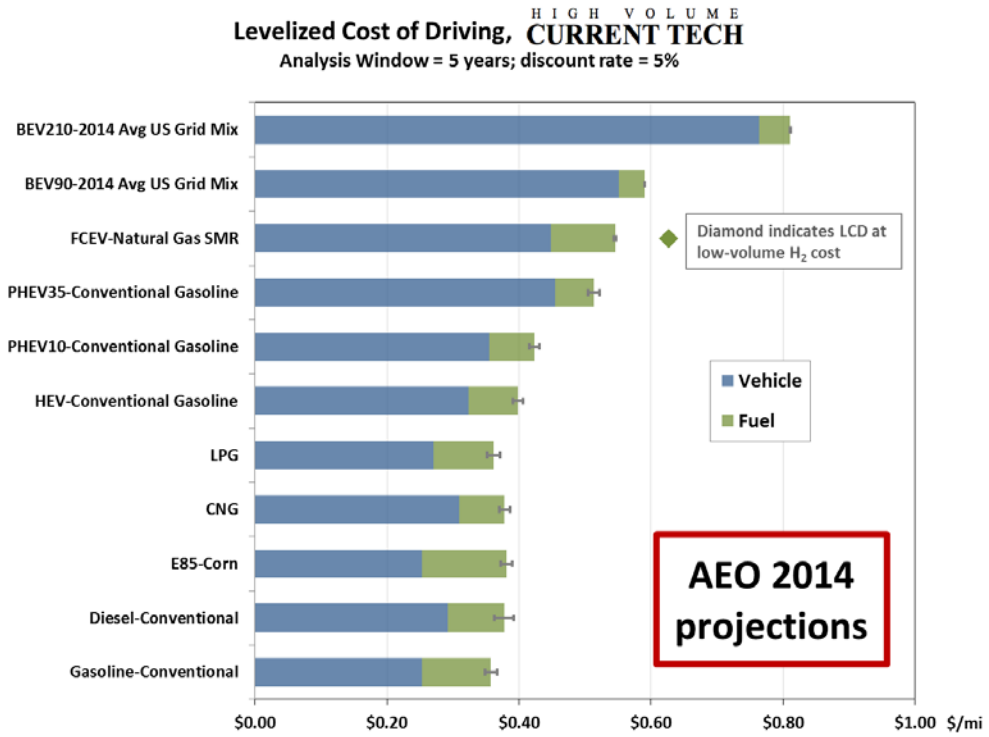

Figure F.1. LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY case using AEO 2014 cost projections

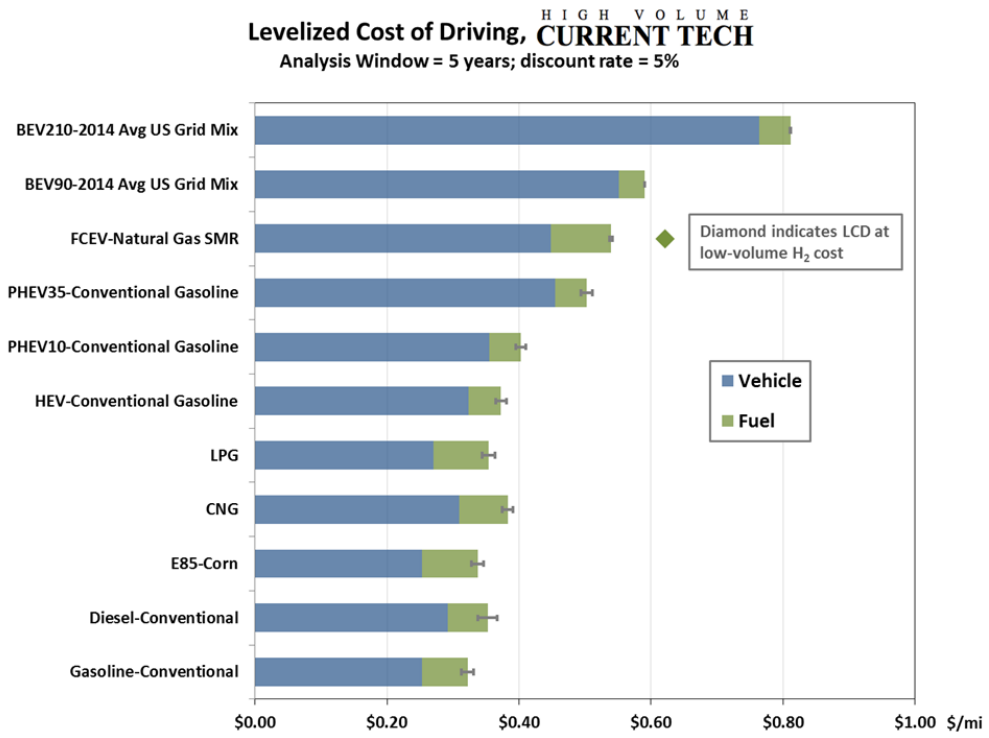

Figure 22 (repeated here). LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY case using AEO 2015 cost projections

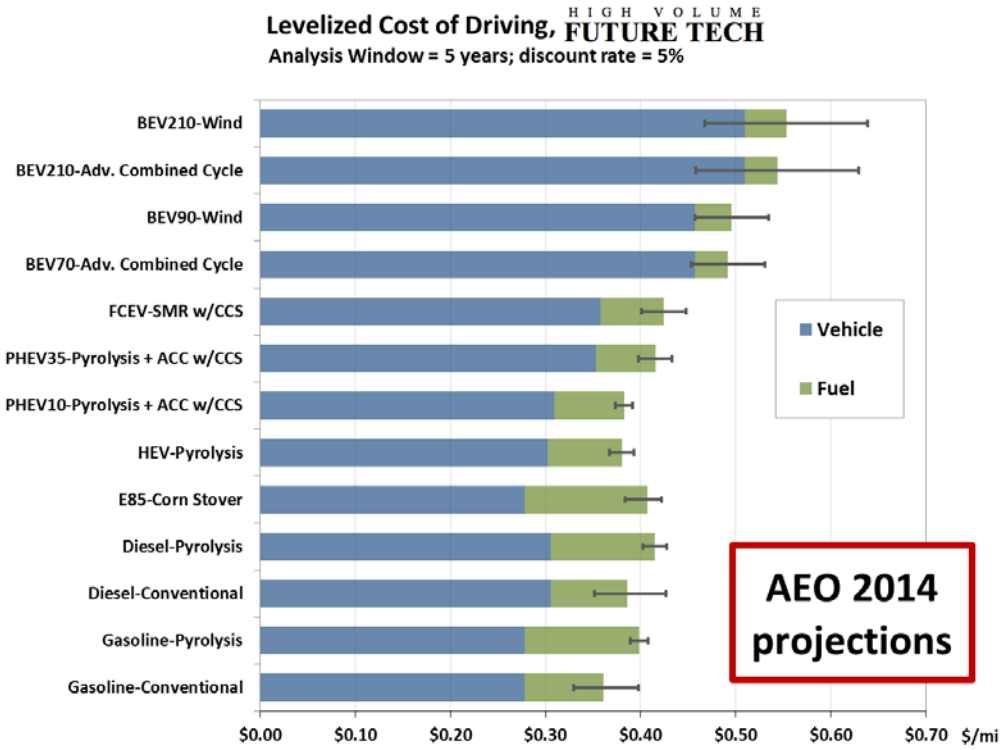

Figure F.2. LCD by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case using AEO 2014 cost projections

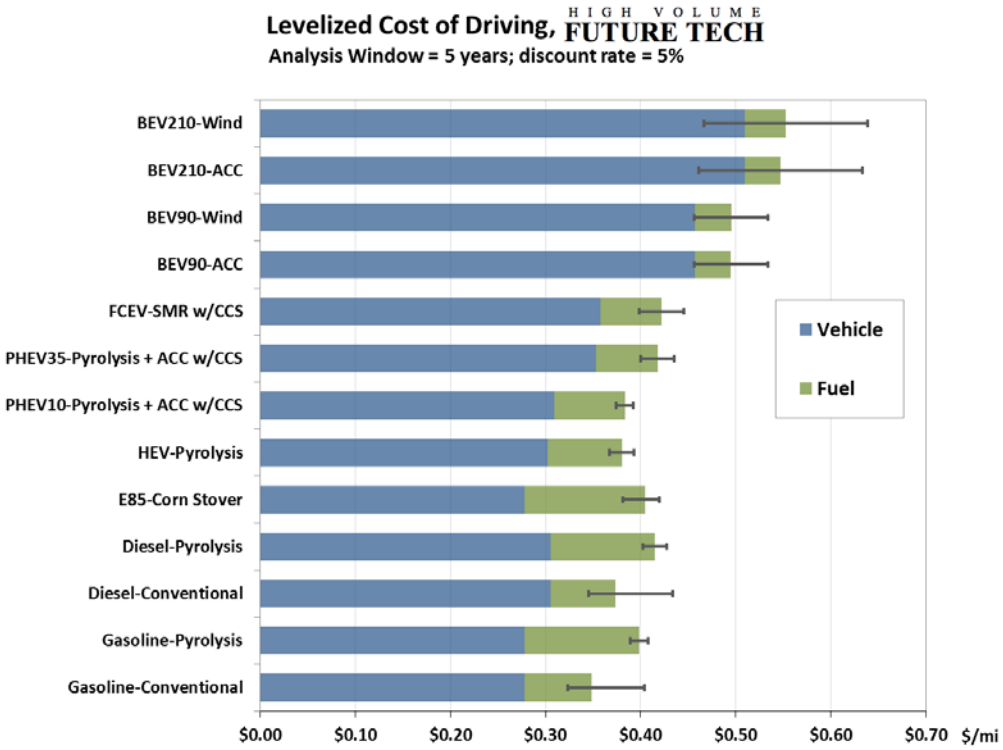

Figure 23 (repeated here). LCD by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case using AEO 2015 cost projections

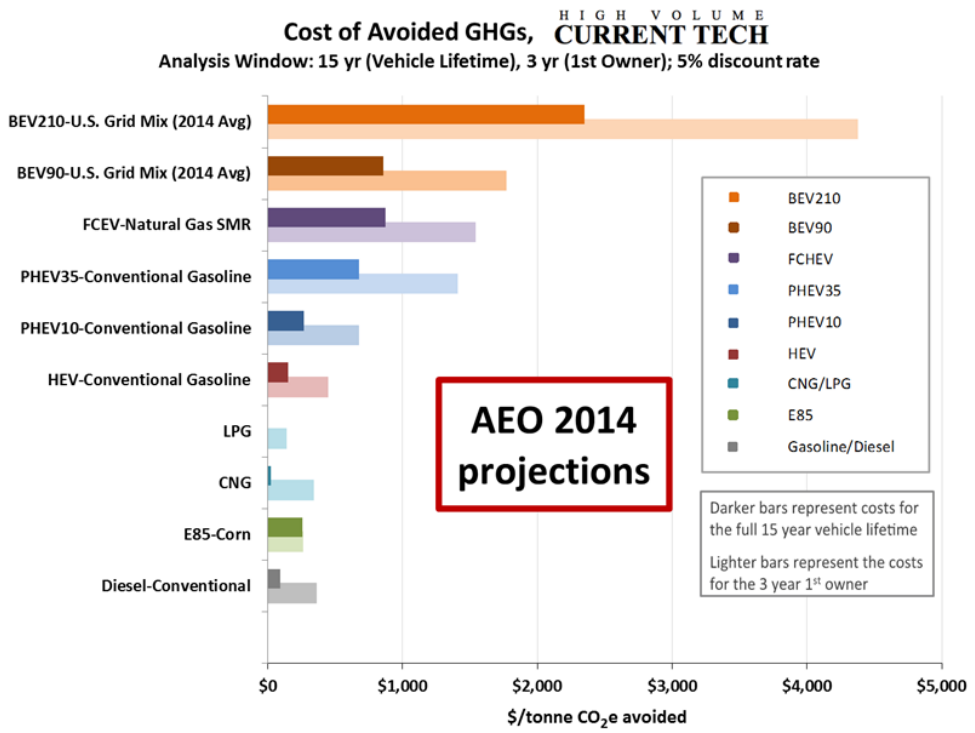

Figure F.3. Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case, relative to the CURRENT TECHNOLOGY gasoline ICEV, using AEO 2014 cost projections

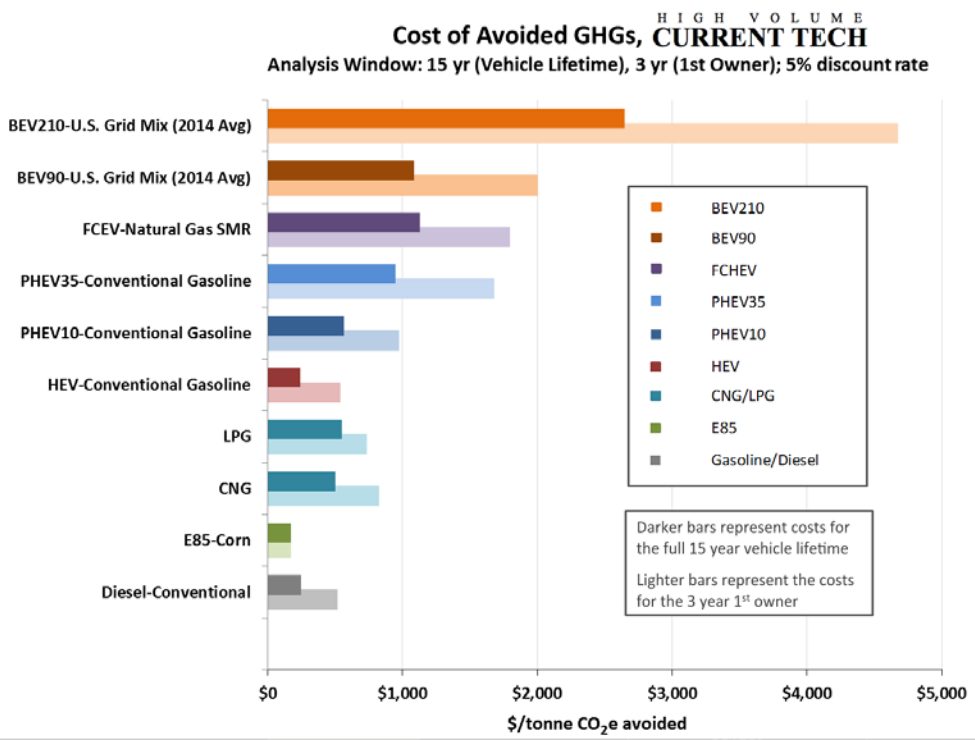

Figure 33 (repeated here). Cost of avoided GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY, HIGH VOLUME case, relative to the CURRENT TECHNOLOGY gasoline ICEV, using AEO 2015 cost projections

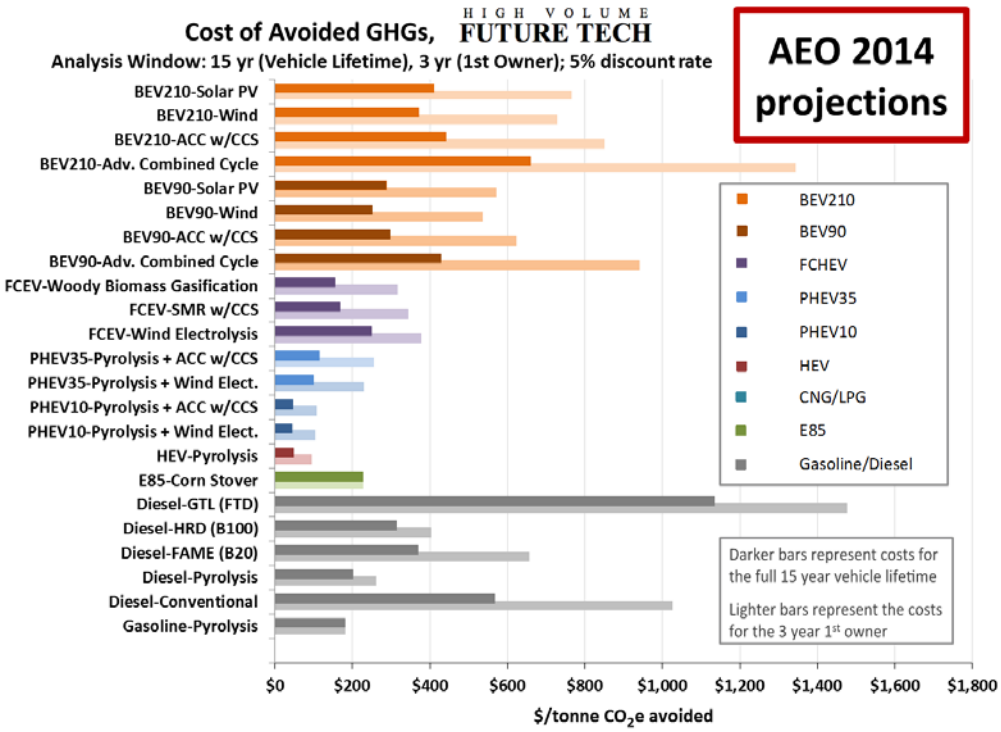

Figure F.4. Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case, relative to the FUTURE TECHNOLOGY gasoline ICEV, using AEO 2014 cost projections

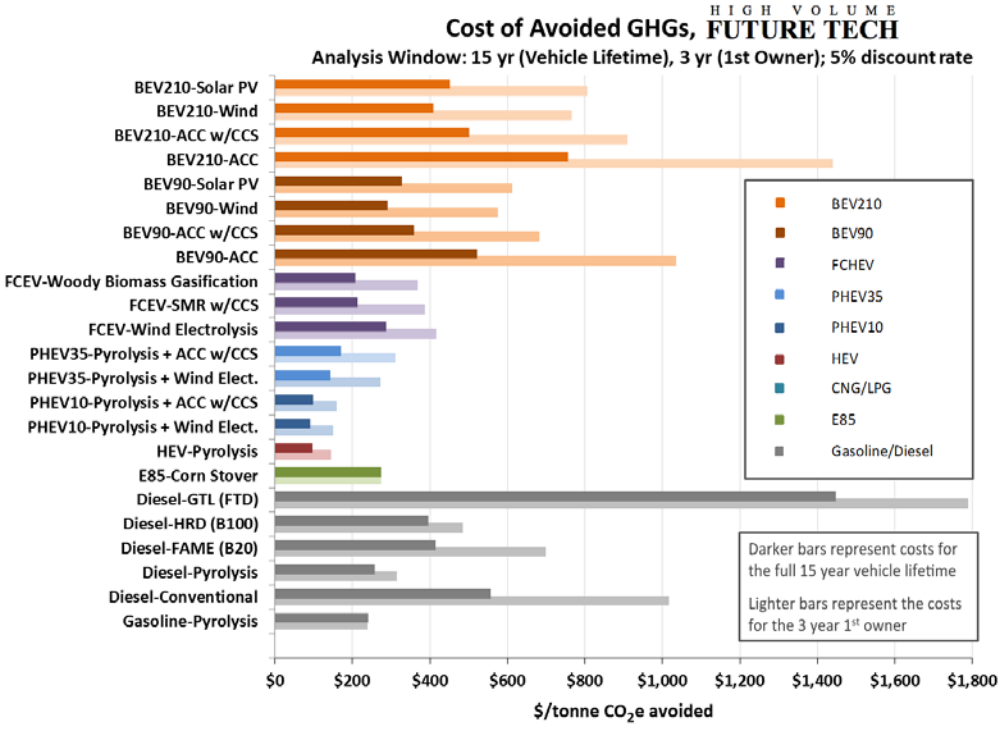

Figure 34 (repeated here): Cost of avoided GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY, HIGH VOLUME case, relative to the FUTURE TECHNOLOGY gasoline ICEV, using AEO 2015 cost projections

Appendix G: Compilation of All References Used in this Report

AFDC (Alternative Fuels Data Center), 2015. *E85*. http://www.afdc.energy.gov/fuels/ethanol_e85.html

Aluminum Association, 1998. *Life Cycle Inventory Report for the North American Aluminum Industry*. Aluminum Association, Washington, DC.

Aluminum Association, 2013. *The Environmental Footprint of Semi-Finished Aluminum Products in North America*. Washington, DC. http://www.aluminum.org/sites/default/files/LCA_Report_Aluminum_Association_12_13.pdf

API (American Petroleum Institute), 2014. *Gasoline Tax*. http://www.api.org/oil-and-natural-gas-overview/industry-economics/fuel-taxes/gasoline-tax

Argonne National Laboratory, Systems Assessment Group, 2014. *GREET Model, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. https://greet.es.anl.gov/index.php

Argonne, 2015. *GCTool: Design, Analyze and Compare Fuel Cell Systems and Power Plants*. http://www.anl.gov/technology/project/gctool-design-analyze-and-compare-fuel-cell-systems-and-power-plants

ASTM (American Society for Testing and Materials) International, 2010. *ASTM D5975-96, Standard Test Method for Determining the Stability of Compost by Measuring Oxygen Consumption*. ASTM International, West Conshohocken, PA. http://www.astm.org/Standards/D5975.htm

ASTM International, 2015. *ASTM D5798-15, Standard Specification for Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines*. ASTM International, West Conshohocken, PA. http://www.astm.org/Standards/D5798.htm

ATLASS Consortium, 2011. *Assessing the Land Use Change Consequences of European Biofuel Policies*. http://trade.ec.europa.eu/doclib/html/148289.htm

Babcock, E., A. Elaahi, and H.E. Lowitt, 1988. *The U.S. Glass Industry: An Energy Perspective*. Report DOE/RL/01830-T60, Pacific Northwest Laboratory, Richland, WA.

BEA (Bureau of Economic Analysis), U.S. Department of Commerce, 2015. *National Income and Produce Account Tables*. http://www.bea.gov/iTable/iTableHtml.cfm?reqid=9&step=3&isuri=1&903=13

Berry, R., and M.F. Fels, 1972. *The Production and Consumption of Automobiles*. Illinois Institute for Environmental Quality, Springfield, IL.

BNEF (Bloomberg New Energy Finance), 2013. *Cellulosic Ethanol Heads for Cost-Competitiveness by 2016*. http://about.bnef.com/press-releases/cellulosic-ethanol-heads-for-cost-competitiveness-by-2016/

Bomgardner, M.M., 2013. "Building a New Biofuels Industry." *Chemical & Engineering News*, Vol. 91, Issue 4: 20–22. http://cen.acs.org/articles/91/i4/Building-New-Biofuels-Industry.html

Borglum, G.B., 1980. *Starch Hydrolysis for Ethanol Production*. https://web.anl.gov/PCS/acsfuel/preprint%20archive/Files/25_4_SAN%20FRANCISCO_08-80_0264.pdf

Brinkman, N., M. Wang, T. Weber, T. Darlington, 2005. *GM Study: Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions*. https://greet.es.anl.gov/publication-4mz3q5dw

Brown, H.L., B.B. Hamel, B.A. Hedman, M. Koluch, B.C. Gajanana, and P. Troy, 1996. *Energy Analysis of 108 Industrial Processes*. The Fairmont Press, Inc.

BSI (British Standards Institution), 2011. *Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*. British Standard PAS 2050:2011, London, U.K. http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf

Burnham, A., M.Q. Wang, and Y. Wu, 2006. *Development and Applications of GREET 2.7 - The Transportation Vehicle-Cycle Model* Report ANL/ESD/06-5, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-lkldbrwj

Burnham, A., 2012. *Updated Vehicle Specifications in the GREET Vehicle-Cycle Model*. Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-update-veh-specs

Burnham, A., J. Han, A. Elgowainy, and M. Wang, 2014. *Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET1_2014 Model*. https://greet.es.anl.gov/publication-emissions-ng-2014

Cai, H., M.Q. Wang, A. Elgowainy, and J. Han, 2012. *Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors and Their Probability Distribution Functions for Electric Generating Units*. Report ANL/ESD/12-2, Center for Transportation Research, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-updated-elec-emissions

Cai, H., M. Wang, A. Elgowainy, and J. Han, 2013. *Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors of the U.S. Electric Generating Units in 2010.* Argonne National Laboratory. https://greet.es.anl.gov/publication-electricity-13

Cai, H., J. Han, A. Elgowainy, and M. Wang, 2014. *Updated Vented, Flaring, and Fugitive Greenhouse Gas Emissions for Crude Oil Production in the GREET™ Model*. https://greet.es.anl.gov/publication-emissions-crude-oil-2014

Cai, H., A.R. Brandt, S. Yeh, J.G. Englander, J. Han, and A. Elgowainy, 2015. "Well-to-Wheels Greenhouse Gas Emissions of Canadian Oil Sands Products: Implications for U.S. Petroleum Fuels." *Environ. Sci. & Technol*., 49 (13), 8219–8227, DOI: 10.1021/acs.est.5b01255. http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01255

CARB (California Air Resources Board), 2009. "Proposed Regulation for Implementing Low Carbon Fuel Standards," In: *Staff Report: Initial Statement of Reasons, vol. 1*, California Environmental Protection Agency, Sacramento, CA, March 5.

CARB, 2015. *Low Carbon Fuel Standard Regulation*. http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

Cao, Q., S. Pagerit, R.B. Carlson, and A. Rousseau, 2007. "PHEV Hymotion Prius Model Validation and Control Improvements," In: *23rd International Electric Vehicle Symposium (EVS23)*. Anaheim, CA.

Carlson, E., 2004. TIAX, Cambridge, Mass., Personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, IL.

Cazzola, P., G. Morrison, H. Kaneko, F. Cuenot, A. Ghandi, and L. Fulton, 2013. *Production Costs of Alternative Transportation Fuels, International Energy Agency*. Paris, France. http://www.iea.org/publications/freepublications/publication/production-costs-of-alternative-transportation-fuels-influence-of-crude-oil-price-and-technology-maturity-.html

Cooper, J.S., 2004. *Recyclability of Fuel Cell Power Trains*. Presented at SAE 2006 World Congress, Detroit, MI. doi:10.4271/2004-01-1136. http://dx.doi.org/10.4271/2004-01-1136

Cuenca, R., J. Formento, L. Gaines, B. Marr, D. Santini, M. Wang, S. Adelman, D. Kline, J. Mark, J. Ohi, N. Rau, S. Freeman, K. Humphreys, and M. Placet, 1998. *Total Energy Cycle Assessment of Electric and Conventional Vehicles: An Energy and Environmental Analysis*. Report ANL/ES/RP-96387, Argonne National Laboratory, Argonne, IL. http://dx.doi.org/10.2172/627823

Cuenca, R., 2005. Argonne National Laboratory, Personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, IL.

Davis, R., L. Tao, E.C.D. Tan, M.J. Biddy, G.T. Beckham, C. Scarlata, J. Jacobson, K. Cafferty, J. Ross, J. Lukas, D. Knorr, and P. Schoen, 2013. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*. Report TP-5100-60223, NREL. http://www.nrel.gov/docs/fy14osti/60223.pdf

Deng, L., C.W. Babbitt, and E.D. Williams, 2011. "Economic-balance Hybrid LCA Extended with Uncertainty Analysis: Case Study of a Laptop Computer." *J. Clean. Prod*., 19, 1198–1206, doi:10.1016/j.jclepro.2011.03.004. http://dx.doi.org/10.1016/j.jclepro.2011.03.004

Denholm, P., M. Hand, M. Jackson, and S. Ong, 2009. *Land-Use Requirements of Modern Wind Power Plants in the United States*. Report TP-6A2-45834, NREL. http://www.nrel.gov/docs/fy09osti/45834.pdf

Diebold, J.P., 2002. "A Review of the Chemical and Physical Mechanisms of the Storage Stability of Fast Pyrolysis Bio-oils." In: *Fast Pyrolysis of Biomass: A Handbook*, A. Bridgwater (ed.), CPL Press: Newbury, U.K., Vol. 2, pp. 243–292.

DOE (U.S. Department of Energy), 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. R.D. Perlack and B.J. Stokes (Leads), Report ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN. 227 pp. http://www.energy.gov/eere/bioenergy/downloads/us-billion-ton-update-biomass-supply-bioenergy-and-bioproducts-industry

DOE, Office of Environmental Management, 2013a. *Technology Readiness Assessment (TRA) / Technology Maturation Plan (TMP) Process Implementation Guide*. http://energy.gov/em/downloads/technology-readiness-assessment-tratechnology-maturation-plan-tmp-process-guide

DOE, Hydrogen and Fuel Cells Program, 2013b. *Record 13010: Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost*. https://www.hydrogen.energy.gov/program_records.html

DOE, 2014a. *Abengoa*. http://www.energy.gov/eere/bioenergy/abengoa

DOE, 2014b. *Bioenergy Technologies Office Multi-Year Program Plan*. July. http://www.energy.gov/sites/prod/files/2014/07/f17/mypp_july_2014.pdf

DOE, Hydrogen and Fuel Cells Program, 2015a. *Production Case Studies*. https://www.hydrogen.energy.gov/h2a_prod_studies.html

DOE, Hydrogen and Fuel Cells Program, 2015b. *DOE H2A Delivery Analysis*. https://www.hydrogen.energy.gov/h2a_delivery.html

DOE, Hydrogen and Fuel Cells Program, 2015c. *DOE H2A Production Analysis*. https://www.hydrogen.energy.gov/h2a_production.html

DOE, Hydrogen and Fuel Cells Program, 2015d. *Record 15015: Fuel Cell System Cost – 2015*. https://www.hydrogen.energy.gov/program_records.html

Dunn, J.B., S. Mueller, and M.Q. Wang, 2012a. "Energy Consumption and Greenhouse Gas Emissions from Enzyme and Yeast Manufacture for Corn and Cellulosic Ethanol Production." *Biotechnol. Lett*., doi: 10.1007/s10529-012-1057-6. http://link.springer.com/article/10.1007%2Fs10529-012-1057-6

Dunn, J., L. Gaines, M. Barnes, J. Sullivan, and M. Wang, 2012b. *Material and Energy Flows in the Materials Production, Assembly, and End of Life Stages of the Automotive Lithium Ion Battery Life Cycle*. Report ANL/ESD/12-3, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-lib-lca

Dunn, J.B., et al., 2013. Argonne National Laboratory, unpublished information.

Dunn, J.B., Z. Qin, S. Mueller, H. Kwon, M.M. Wander, and M. Wang, 2014a. *Carbon Calculator for Land Use: Change from Biofuels Production (CCLUB).* Report ANL/ESD/12-5, Rev. 2, Argonne National Laboratory. https://greet.es.anl.gov/publication-cclub-manual

Dunn, J., L. Gaines, M. Barnes, J. Sullivan, and M. Wang, 2014b. *Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle*. Report ANL/ESD/12-3 Rev., Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-li-ion

Dunn, J., L. Gaines, J.C. Kelly, C. James, and K.G. Gallagher, 2014c. "The Significance of Li-ion Batteries in Electric Vehicle Life-cycle Energy and Emissions and Recycling's Role in Its Reduction." *Energy Environ. Sci*., 8, 158–168. doi:10.1039/C4EE03029J. http://dx.doi.org/10.1039/C4EE03029J

Dunn, J., C. James, L. Gaines, K. Gallagher, Q. Dai, and J.C. Kelly, 2015. *Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries*. Report ANL/ESD-14/10, Rev., Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-anode-cathode-liion

Elgowainy, A., J. Han, L. Poch, M. Wang, A. Vyas, M. Mahalik, and A. Rousseau, 2010. *Well-to-wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles*. Report ANL-ESD-10-1, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-xkdaqgyk

Elgowainy, A., J. Han, and H. Zhu, 2013. *Updates to Parameters of Hydrogen Production Pathways in GREET*. Research note, Argonne National Laboratory. https://greet.es.anl.gov/publication-h2-13

Elgowainy, A., J. Han, H. Cai, M. Wang, G.S. Forman, and V.B. DiVita, 2014. "Energy Efficiency and Greenhouse Gas Emissions Intensity of Petroleum Products at US Refineries," *Environ. Sci. and Technol*., doi: 10.1021/es5010347. http://pubs.acs.org/doi/abs/10.1021/es5010347

Elliott, J., B. Sharma, N. Best, M. Glotter, J.B. Dunn, I. Foster, F. Miguez, S. Mueller, and M. Wang, 2014. "A Spatial Modeling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions." *Environ. Sci. Technol*., 48 (4), pp. 2488–2496. DOI: 10.1021/es404546r. http://pubs.acs.org/doi/abs/10.1021/es404546r

Englander, J.G., and A.R. Brandt, 2014. *Oil Sands Energy Intensity Analysis for GREET Model Update*.

Espinosa, N., R. García-Valverde, and F.C. Krebs, 2011. "Life-cycle Analysis of Product Integrated Polymer Solar Cells." *Energy Environ. Sci*., 4, 1547–1557. doi:10.1039/C1EE01127H. http://dx.doi.org/10.1039/C1EE01127H

EC (European Community), 2009a. *Directive 2009/28/EC of the European Parliament and of the Council, on the Promotion of the Use of Energy from Renewable Sources*. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028

EC, 2009b. *Directive 2009/30/EC of the European Parliament and of the Council, on the Specification of Petrol, Diesel and Gas-oil and Introducing a Mechanism to Monitor and Reduce Greenhouse Gas Emissions*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0030

EIA (Energy Information Administration), 2013a. *Form EIA-923 Detailed Data*. http://www.eia.gov/electricity/data/eia923

EIA, 2013b. *Refinery Capacity Report 2013*. Table 10a, Washington, DC. http://www.eia.gov/petroleum/refinerycapacity/archive/2013/table10.pdf

EIA, 2014a. *Annual Energy Outlook 2014 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf

EIA, 2014b. *Crude Oil Production*. http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm

EIA, 2015a. *Annual Energy Outlook 2015 with Projections to 2040*. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

EIA, 2015b. *Assumptions to the Annual Energy Outlook 2015*. http://www.eia.gov/forecasts/aeo/assumptions/pdf/liquidfuels.pdf

EIA, 2015c. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015*. https://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

EIA, 2016a. *Monthly Energy Review*. http://www.eia.gov/totalenergy/data/monthly/

EIA, 2016a. *Petroleum and Other Liquids; Cushing, OK WTI Spot Price FOB*. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RWTC&f=D

EIA, 2016b. *Petroleum and Other Liquids; Gasoline and Diesel Fuel Update*. http://www.eia.gov/petroleum/gasdiesel/

EPA (U.S. Environmental Protection Agency), 2006. *Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates, Final Technical Support Document*. Report EPA420-R-06-017, Washington, DC. http://www3.epa.gov/carlabel/documents/420r06017.pdf

EPA, 2010a. "Regulation of Fuels and Fuel Additives: 2011 Renewable Fuel Standards." *Federal Register*, December 9, Vol. 75 (No. 236): 76790–76830. https://www.federalregister.gov/articles/2010/12/09/2010-30296/regulation-of-fuels-and-fuel-additives-2011-renewable-fuel-standards

EPA, 2010b. "Regulations of Fuels and Fuels Additives: Changes to Renewable Fuel Standard Program; Final Rule." *Federal Register*, March 26, Vol. 75 (No. 58): 14670–14904. https://www.federalregister.gov/articles/2010/03/26/2010-3851/regulation-of-fuels-and-fuel-additives-changes-to-renewable-fuel-standard-program

EPA, 2010c. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. Report EPA-420-R-10-006. http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

EPA, 2013. *Air Markets Program Data*. http://ampd.epa.gov/ampd

EPA, Climate Change Division, 2014. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012.* Report EPA 430-R-14-003, Washington, DC. http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html#fullreport

EPA, 2015a. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990–2013*. Report EPA-420-F-15-032. https://www.epa.gov/sites/production/files/2016-02/documents/420f15032.pdf

EPA, 2015b. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015*. Report EPA-420-R-15-016. http://www3.epa.gov/fueleconomy/fetrends/1975-2015/420r15016.pdf

EPA, 2016a. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013*. Report EPA 430-R-16-002. https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Main-Text.pdf

Francfort, J., B. Bennett, R. Carlson, T. Garretson, L.L. Gourley, D. Karner, M. Kirkpatrick, P. McGuire, D. Scoffield, M. Shirk, S. Salisbury, S. Schey, J. Smart, S. White, and J. Wishart, 2015. *Plug-in Electric Vehicle and Infrastructure Analysis*. Report INL/EXT-15-35708, Idaho National Laboratory. http://avt.inel.gov/summaryreport.shtml

Franklin Associates, 2001. *A Life Cycle Inventory of Selected Commercial Roofing Products*. Athena™ Sustainable Materials Institute, Ottawa, ON, Canada. http://www.athenasmi.org/wp-content/uploads/2011/10/4_Commercial_Roofing_Products.pdf

Franklin Associates, 2011. *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*. American Chemistry Council (ACC), Plastics Division, Washington, DC. http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only

Fthenakis, V., W. Wang, and H.C. Kim, 2007. *Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics.* Report BNL-77919-2007, Brookhaven National Laboratory, Upton, NY. http://dx.doi.org/10.2172/909957

Fthenakis, V., W. Wang, and H.C. Kim, 2009. "Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics." *Renew. Sustain. Energy Rev*., 13, 493–517. doi:10.1016/j.rser.2007.11.012. http://dx.doi.org/10.1016/j.rser.2007.11.012

Gabby, P., 2005. *United States Geological Survey Mineral Yearbook*. U.S. Geological Survey, Washington, DC.

Galitsky, C., and E. Worrell, 2008. *Energy Efficiency Improvement and Cost Saving Opportunities for the Vehicle Assembly Industry*. Report LBNL-50939-Revision, Lawrence Berkeley National Laboratory, Berkeley, CA. http://dx.doi.org/10.2172/927881

Gas Technology Institute, Haldor Topsoe, Andritz, UPM, and Phillips 66, 2015. *Green Gasoline from Wood using Carbona Gasification and Topsoe TIGAS Process.* Report DE-EE0002874.

Glauser, J., and Y. Inoguchi, 2011. *Lithium, Lithium Minerals, and Lithium Chemicals.* CEH Marketing Research Report, SRI Consulting, Zurich, Switzerland.

Globe Newswire, 2010. *Abengoa Bioenergy and Mid-Kansas Electric Reach Agreement Concerning First Commercial-Scale Hybrid Cellulosic Ethanol and Power Plant in U.S.* January 19. http://www.globenewswire.com/news-release/2010/01/19/412515/182207/en/Abengoa-Bioenergy-and-

Mid-Kansas-Electric-Reach-Agreement-Concerning-First-Commercial-Scale-Hybrid-Cellulosic-Ethanol-and-Power-Plant-in-U-S.html

Goellner, J.F., V. Shah, M.C. Turner, N.J. Kuehn, J. Littlefield, G. Cooney, and J. Marriott, 2013. *Analysis of Natural Gas-to Liquid Transportation Fuels via Fischer-Tropsch*. Report, DOE/NETL-2013/1597, National Energy Technology Laboratory. http://netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Gas-to-Liquids_Report.pdf

GPO (Government Printing Office), 2007. *Energy Independence and Security Act*. https://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf

GPO, 2010. *Environmental Protection Agency and Department of Transportation: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule*. https://www.gpo.gov/fdsys/pkg/FR-2010-05-07/pdf/2010-8159.pdf

GPO, 2012. *2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule*. https://www.gpo.gov/fdsys/pkg/FR-2012-10-15/pdf/2012-21972.pdf

Gruber, P.W., P.A. Medina, G.A. Keoleian, S.E. Kesler, M.P. Everson, and T.J. Wallington, 2011. "Global Lithium Availability." *J. Ind. Ecol*., 15, 760–775. doi:10.1111/j.1530-9290.2011.00359.x. http://dx.doi.org/10.1111/j.1530-9290.2011.00359.x

Han, J., A. Elgowainy, I. Palou-Rivera, J.B. Dunn, and M.Q. Wang, 2011. *Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET*. Report ANL/ESD/11-8, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-wtw_fast_pyrolysis

Han, J., A. Elgowainy, H. Cai, and M. Wang, 2013a. "Life-cycle Analysis of Bio-based Aviation Fuels." *Bioresource Technology*, Vol. 150, pp. 447–456, doi:10.1016/j.biortech.2013.07.153. http://www.sciencedirect.com/science/article/pii/S0960852413012297

Han, J, A. Elgowainy, J. Dunn, and M. Wang, 2013b. "Life Cycle Analysis of Fuel Production from Fast Pyrolysis of Biomass." *Bioresource Technology*, Vol. 133, pp. 421–428, doi:10.1016/j.biortech.2013.01.141. http://www.sciencedirect.com/science/article/pii/S0960852413001739

Han, J., A. Elgowainy, H. Cai, and M. Wang, 2014. *Update to Soybean Farming and Biodiesel Production in GREET*. Research Note, Argonne National Laboratory. https://greet.es.anl.gov/publication-soybean-biodiesel-2014

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen, 2010. "Effects of US Maize Ethanol in Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses." *Bioscience*, 60:223e31.

Hudson, C.L., 1981. *Energy Requirements for Materials Used in Vehicles Characterized for the TAPCUT Project*. Report ANL/EES-TM-211, Argonne National Laboratory, Argonne, IL.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon, 2011. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*. Report TP-5100-47764, NREL. http://www.nrel.gov/docs/fy11osti/47764.pdf

Huo, H., M. Wang, C. Bloyd, and V. Putsche, 2008. *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*. Report ANL/ESD/08-2, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-e5b5zeb7

IEA (International Energy Agency), 2012. *Electricity/Heat in Chile in 2009*. Electr. Chile 2009. http://www.iea.org/statistics/statisticssearch/report/?country=CHILE&product=electricityandheat&year=2009

IPCC (Intergovernmental Panel on Climate Change), 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.), Cambridge University Press, Cambridge, U.K., and New York, NY, doi:10.1017/CBO9781107415324 http://dx.doi.org/10.1017/CBO9781107415324

IRENA (International Renewable Energy Agency), 2013. *Road Transport: The Cost of Renewable Solutions. IRENA Innovation and Technology Centre.* Bonn, Germany. http://www.irena.org/DocumentDownloads/Publications/Road_Transport.pdf

James, B.D., J.M. Moton, and W.G. Colella, 2014. *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2014 Update*. Strategic Analysis Inc., Arlington, VA.

Johnson, M., I. Palou-Rivera, and E. Frank, 2013. "Energy Consumption During the Manufacture of Nutrients for Algae Cultivation," *Algal Research*, Vol. 2, Issue 4, pp. 426–436, doi:10.1016/j.algal.2013.08.003. http://dx.doi.org/10.1016/j.algal.2013.08.003

Jones, S.B., C. Valkenburg, C.W. Walton, D.C. Elliott, J.E. Holladay, D.J. Stevens, C. Kinchin, and S. Czernik, 2009. *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case*, Report PNNL-18284, Pacific Northwest National Laboratory, Richland, WA. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18284.pdf

Jones S.B., P.A. Meyer, L.J. Snowden-Swan, A.B. Padmaperuma, E. Tan, A. Dutta, J. Jacobson, and K. Cafferty, 2013. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway.* Report PNNL-23053 / NREL/TP-5100-61178, Pacific Northwest National Laboratory, Richland, WA. http://www.nrel.gov/docs/fy14osti/61178.pdf

Jones, S.B., L.J. Snowden-Swan, P.A. Meyer, A.H. Zacher, M.V. Olarte, and C. Drennan, 2014. *Fast Pyrolysis and Hydrotreating: 2013 State of Technology R&D and Projections to 2017*. Report PNNL-23294, Pacific Northwest National Laboratory, Richland, WA. http://dx.doi.org/10.2172/1149669

Joseck, F., and J. Ward, 2014. *Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways*. https://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

Keoleian, G., S. Miller, R. De Kleine, A. Fang, and J. Mosley, 2012. *Life Cycle Material Data Update for GREET Model* Report CSS12-12, University of Michigan, Ann Arbor, MI. https://greet.es.anl.gov/publication-greet2-lca-update

Kim, N., R. Carlson, F. Jehlik, and A. Rousseau, 2009. *Tahoe HEV Model Development in PSAT*, SAE Technical Paper 2009-01-1307, Warrendale, PA.

Kwon, H.-Y., S. Mueller, J.B. Dunn, and M.M. Wander, 2013. "Modeling State-level Soil Carbon Emission Factors under Various Scenarios for Direct Land Use Change Associated with United States Biofuel Feedstock Production." *Biomass and Bioenergy*, 55, 299–310. http://www.sciencedirect.com/science/article/pii/S0961953413000950

Lane, J., 2015. The Pyromaniax, "Class of 2015: The Top 10 Pyrolysis Projects in Renewable Fuels." *Biofuels Digest*, August 3. http://www.biofuelsdigest.com/bdigest/2015/08/03/the-pyromaniax-class-of-2015-the-top-10-pyrolysis-projects-in-renewable-fuels/

Leiby, R., 1993. *Secondary Smelting at East Penn Manufacturing*. Presented at Fifth International Seminar on Battery Waste Management, Deerfield Beach, FL.

Mann, M., and D. Steward, 2012. *Current (2010) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Version 3.0*. National Renewable Energy Laboratory, Golden, CO.

Markus Engineering Services, 2002. *Cradle-to-gate Life Cycle Inventory: Canadian and US Steel Production by Mill Type*. Athena™ Sustainable Materials Institute, Ottawa, ON, Canada. http://www.athenasmi.org/wp-content/uploads/2011/10/1_Steel_Production.pdf

Melaina, M., M. Penev, and D. Heimiller, 2013. *Resource Assessment for Hydrogen Production: Hydrogen Production Potential from Fossil and Renewable Energy Resources*. Report TP-5400-55626, NREL. http://www.nrel.gov/docs/fy13osti/55626.pdf

Mitchell, J., 2011. SCS Systems, Houston, TX, Personal communication with Jennifer Dunn, Argonne National Laboratory, Argonne, IL.

Moawad, A., P. Sharer, and A. Rousseau, 2011. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*. Report ANL/ESD/11-4, Argonne National Laboratory, Argonne, IL. http://www.anl.gov/energy-systems/publication/light-duty-vehicle-fuel-consumption-displacement-potential-2045

Moawad, A., N. Kim, N. Shidore, and A. Rousseau, 2016. *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies*. Report ANL/ESD-15/28, Argonne National Laboratory, Argonne, IL. http://www.autonomie.net/publications/fuel_economy_report.html

Moneypenney, B., 2011. Dow Kokam, Midland, MI, Personal communication with Jennifer Dunn, Argonne National Laboratory, Argonne, IL.

Muir, R., 2005. United States Council for Automotive Research/Vehicle Recycling Partnership (USCAR/VRP), Southfield, Mich., Personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, IL.

Müller-Langer, F., S. Majer, and S. O'Keeffe, 2014. "Benchmarking Biofuels—a Comparison of Technical, Economic and Environmental Indicators." *Energy, Sustainability and Society*, 4:20, DOI: 10.1186/s13705-014-0020-x http://energsustainsoc.springeropen.com/articles/10.1186/s13705-014-0020-x

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013. *Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, U.K., and New York, NY. http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf

NHTSA (National Highway Traffic Safety Administration), National Center for Statistics and Analysis, 2006. *Vehicle Survivability and Travel Mileage Schedules*. http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf

National Petroleum Council, 2012. *Advancing Technology for America's Transportation*. http://www.npc.org/reports/trans.html

Nelson, P.A., K.G. Gallagher, I. Bloom, and D.W. Dees, 2011. *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles*. Report ANL-11/32, Argonne National Laboratory, Argonne, IL. http://dx.doi.org/10.2172/1027714

Nelson, P.A., K.G. Gallagher, I. Bloom, and D.W. Dees, 2012. *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Second Edition*. Report ANL-12/55, Argonne National Laboratory. http://www.cse.anl.gov/batpac/files/BatPaC%20ANL-12_55.pdf

Notter, D.A., M. Gauch, R. Widmer, P. Wäger, A. Stamp, R. Zah, and H.-J. Althaus, 2010. "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles." *Environ. Sci. Technol*., 44, 6550–6556, doi:10.1021/es903729a. http://dx.doi.org/10.1021/es903729a

Oasmaa A., and E. Kuoppala, 2003. "Fast Pyrolysis of Forestry Residue. 3. Storage Stability of Liquid Fuel." *Energy & Fuels 2003*, 17, 1075–1084, doi: 10.1021/ef030011o. http://pubs.acs.org/doi/abs/10.1021/ef030011o

Omni Tech International, 2010. *Life Cycle Impact of Soybean Production and Soy Industrial Products*. United Soybean Board, Chesterfield, MO. http://biodiesel.org/reports/20100201_gen-422.pdf

Ong, S., C. Campbell, P. Denholm, R. Margolis, and G. Heath, 2013. *Land-Use Requirements for Solar Power Plants in the United States*. Report TP-6A20-56290, NREL. http://www.nrel.gov/docs/fy13osti/56290.pdf

Pasquier, M., M. Duoba, and A. Rousseau, 2001. "Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedure." In: *The 18th International Electric Vehicle Symposium (EVS18)*. Berlin, Germany.

PE Americas, 2010. *Life Cycle Impact Assessment of Aluminum Beverage Cans*. Aluminum Association, Inc., Washington, DC. http://www.container-recycling.org/assets/pdfs/aluminum/LCA-2010-AluminumAssoc.pdf

Pearlson, M., C. Wollersheim, and J. Hileman, 2013. "A Techno-economic Review of Hydroprocessed Renewable Esters and Fatty Acids for Jet Fuel Production." *Biofuels, Bio-Products, & Bio-Refining*, 7:89–96. John Wiley & Sons. http://dx.doi.org/10.1002/bbb.1378

Plastics Europe, 2010. *Eco-Profiles*. http://www.plasticseurope.org/plasticssustainability/eco-profiles.aspx

Pradhan, A., D.S. Shrestha, A. McAloon, W. Yee, M. Haas, and J.A. Duffield, 2011. "Energy Life-cycle Assessment of Soybean Biodiesel Revisited." *American Society of Agricultural and Biological Engineers*, 54(3), pp. 1031–1039. http://dx.doi.org/10.13031/2013.37088

Qin, Z., J.B. Dunn, H. Kwon, S. Mueller, and M.M. Wander, 2016. "Soil Carbon Sequestration and Land Use Change Associated with Biofuel Production: Empirical Evidence." *GCB Bioenergy*, 8: 66–80, doi:10.1111/gcbb.12237 http://dx.doi.org/10.1111/gcbb.12237

Ramsden, T., M. Ruth, V. Diakov, M. Laffen, and T.A. Timbario, 2013. *Hydrogen Pathways Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios*. Report NREL/TP-6A10-60528, National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy14osti/60528.pdf

Rousseau, A., 2000. “Simulation and Validation of Hybrid Electric Vehicles Using AUTONOMIE.” In: *The 3rd Global Powertrain Congress*, Detroit, MI.

Rousseau, A., J. Kwon, P. Sharer, S. Pagerit, and M. Duoba, 2006. *Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT*. SAE Technical Paper 2006-01-0667, Warrendale, PA.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu, 2008. “Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change.” *Science*, 319(5867), pp. 1238–1240, DOI: 10.1126/science.1151861. http://science.sciencemag.org/content/319/5867/1238.abstract

Sheehan J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelsh, 2008. “Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol.” *J. of Ind. Ecol*., 7(3–4):117–46.

Shuster, E., et al., 2013. *Analysis of Natural Gas-to-Liquid Transportation Fuels via Fischer-Tropsch*. Report DOE/NETL-2013/1597, National Energy Technology Laboratory. http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Gas-to-Liquids_Report.pdf

SAE (Society for Automotive Engineers) International, 2010. *Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data*. http://standards.sae.org/j2841_201009/

SQM, 2001. Capitulo 2 Descripcion del Proyecto. Capitulo 2 Descripcion Proy. http://seia.sea.gob.cl/expediente/expedientesEvaluacion.php?modo=ficha&id_expediente=3521#-1

Stephens, T., Y. Zhou, A. Elgowainy, M. Duoba, A.D. Vyas, and A. Rousseau, 2013. *Estimating On-Road Fuel Economy of PHEVs from Test and Aggregated Data*. Presented at the Transportation Research Board 92nd Annual Meeting.

Stodolsky, F., A. Vyas, R. Cuenca, and L. Gaines, 1995. *Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles*. Presented at 1995 Total Life Cycle Conference & Exposition, Vienna, Austria.

Sullivan, J.L., R.L. Williams, S. Yester, E. Cobas-Flores, S.T. Chubbs, S.G. Hentges, and S.D. Pomper, 1998. *Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project*. SAE Technical Paper 982160, Warrendale, PA. http://papers.sae.org/982160/

Sullivan, J., A. Burnham, and M. Wang, 2010. *Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing*. Report ANL/ESD/10-6, Argonne National Laboratory, Argonne, IL. https://greet.es.anl.gov/publication-vehicle_and_components_manufacturing

Sutter, J., 2007. *Life Cycle Inventories of Petrochemical Solvents*. Swiss Centre for Life Cycle Inventories, Zurich, Switzerland.

Tagawa, K., and R.J. Brodd, 2009. “Production Processes for Fabrication of Lithium-Ion Batteries.” In: M. Yoshio, R.J. Brodd, A. Kozawa, (eds.), *Lithium-Ion Batteries Science and Technologies*. Springer, New York, NY.

Taheripour, F., and W.E. Tyner, 2013. “Biofuels and Land Use Change: Applying Recent Evidence to Model Estimates.” *Applied Sciences*, 3, 14–38. http://www.mdpi.com/2076-3417/3/1/14

Tao, L., D. Schell, R. Davis, E. Tan, R. Elander, and A. Bratis, 2014. *NREL 2012 Achievement of Ethanol Cost Targets: Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*. Report NREL/TP-5100-61563, NREL. http://www.nrel.gov/docs/fy14osti/61563.pdf

Tyner, W.E., F. Taheripour, Q. Zhuang, D. Birur, and U. Baldos, 2010. *Land Use Changes and Consequent CO_2 Emissions Due to US Corn Ethanol Production: A Comprehensive Analysis*. Purdue University, Department of Agricultural Economics. https://www.gtap.agecon.purdue.edu/resources/download/5200.pdf

USDA (U.S. Department of Agriculture), 2013. *NASS Highlights: 2012 Agricultural Chemical Use Survey, Soybean*. Washington, DC. http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2012_Soybeans_Highlights/ and http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/index.php

USDA, Economic Research Service (2015). *U.S. Bioenergy Statistics*. http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx

U.S. DRIVE Partnership, 2013. *Electrochemical Energy Storage Technical Team Roadmap*. http://energy.gov/eere/vehicles/downloads/us-drive-electrochemical-energy-storage-technical-team-roadmap

USGS (U.S. Geological Survey), 2006. *US Coal Quality Database (Version 2.0), National Coal Resources Data System*. http://energy.er.usgs.gov/products/databases/CoalQual/index.htm

USA, 2015. *Intended Nationally Determined Contribution (INDC) Submitted to the United Nations*. March 31. http://www4.unfccc.int/submissions/INDC/Published%20Documents/United%20States%20of%20America/1/U.S.%20Cover%20Note%20INDC%20and%20Accompanying%20Information.pdf

Van Deusen, P., and L.S. Heath, 2013. *COLE Web Applications Suite*. NCASI and USDA Forest Service, Northern Research Station. http://www.ncasi2.org/COLE/

Wang, M., H. Huo, and S. Arora, 2011. "Methods of Dealing with Co-products of Biofuels in Life-cycle Analysis and Consequent Results within the U.S. Context." *Energy Policy*, 39, 5726–5736. http://www.sciencedirect.com/science/article/pii/S0301421510002156

Wang, M., J. Han, J. Dunn, H. Cai, and A. Elgowainy, 2012. "Well-to-wheels Energy Use and Greenhouse Gas Emissions of Ethanol from Corn, Sugarcane and Cellulosic Biomass for US Use," *Environmental Research Lett.*, Vol. 7, No. 4, 045905. http://dx.doi.org/10.1088/1748-9326/7/4/045905

Wang, Z., D. Dunn, J. Han, and M. Wang, 2013. *Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels for GREET1_2013*. Report ANL/ESD-13/9, Argonne National Laboratory. https://greet.es.anl.gov/publication-feedstocks-13

Wang, Z., D. Dunn, and M. Wang, 2014. *Updates to the Corn Ethanol Pathway and Development of an Integrated Corn and Corn Stover Ethanol Pathway in the GREET Model*. Report ANL/ESD-14/11, Argonne National Laboratory. https://greet.es.anl.gov/publication-update-corn-ethanol-2014

Ward's Auto, 2016. Ward's U.S. Light Vehicle Market Segmentation and Prices, '15 Model Year. http://wardsauto.com/datasheet/wards-us-light-vehicle-market-segmentation-and-prices-15-model-year

Weissler, P., 2009. "Many Factors Figure in Fuel-economy Calculation for Electric Vehicles." *Automot. Eng. Mag.*, 41.

White House, Executive Office of the President, 2013a. *The President's Climate Action Plan*. https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf

White House, Interagency Working Group on Social Cost of Carbon, 2013b. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under*

Executive Order 12866. https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf

Wood, R.A., R.A. Boardman, M.W. Patterson, and P.M. Mills, 2010. *HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Economic Analysis*. Report TEV-954, Idaho National Laboratory.

Wright, M.M., J.A. Satrio, R.C. Brown, D.E. Daugaard, and D.D. Hsu, 2010. *Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels*. Report NREL/TP-6A20-46586, National Renewable Energy Laboratory, Golden, CO. http://www.nrel.gov/docs/fy11osti/46586.pdf

Xie, X., M. Wang, and J. Han, 2011. "Assessment of Fuel-Cycle Energy Use and Greenhouse Gas Emissions for Fischer-Tropsch Diesel from Coal and Cellulosic Biomass." *Environ. Sci. Technol*., 45, 3047–3053. http://dx.doi.org/10.1021/es1017703

Energy Systems Division
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4854

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC