ANL-22/27 Rev.1

Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030-2035) Technologies

Energy Systems Division

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Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030-2035) Technologies

by
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U.S. DRIVE Integrated Systems Analysis Technical Team 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, other participating National Laboratories, the U.S. Department of Energy, or the U.S. DRIVE partners.

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ACRONYMS AND INITIALISMS

ABS	acrylonitrile butadiene styrene
ACC	advanced combined cycle
AEO	Annual Energy Outlook
API	American Petroleum Institute
ASCM	Automotive System Cost Model
ASTM	American Society of Testing and Materials
BatPaC	Battery Performance and Cost [model]
BETO	United States Department of Energy, Bioenergy Technologies Office
BEV	battery electric vehicle
BMS	battery management system
BOL	beginning of life
C2G	cradle-to-grave
CCLUB	Carbon Calculator for Land Use Change from Biofuels
CCS	carbon capture and storage
CD	charge depleting
CFP	catalytic fast pyrolysis
CFRP	carbon fiber reinforced plastic
CHP	combined heat and power
CNG	compressed natural gas
CO_2e	CO_2-equivalent
COG	coke oven gas
CS	charge sustaining
DGS	distillers' grains and solubles
DOE	Department of Energy
EGU	electric generating unit
EIA	Energy Information Administration
EOL	end-of-life
EPA	Environmental Protection Agency
EPDM	ethylene propylene diene monomer
EREV	extended-range electric vehicle
EVSE	electric vehicle supply equipment
FAME	fatty acid methyl ester
FCEV	fuel cell electric vehicle
FFV	flexible fuel vehicle
FT	Fischer-Tropsch
FTD	Fischer-Tropsch diesel
GHG	greenhouse gas
GPPS	general purpose polystyrene
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation [model]

GTAP	Global Trade Analysis Project
GTL	gas-to-liquid
GTL FTD	gas-to-liquid Fischer-Tropsch diesel
GVW	gross vehicle weight
GWP	global warming potential
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
IRR	internal rate of return
LCA	life cycle analysis
LCD	levelized cost of driving
LDPE	low-density polyethylene
LDV	light-duty vehicles
LFP-G	lithium iron phosphate with a graphite electrode
LHV	lower heating value
LLDPE	linear low-density polyethylene
LMC	land management change
LMO-G	lithium manganese oxide spinel with a graphite electrode
LMO-LTO	lithium manganese spinel with a titanium dioxide electrode
LPG	liquefied petroleum gas
LUC	land-use change
MSFP	minimum selling fuel price
MSRP	manufacturer's suggested retail price
MY	model year
NCAG	lithium nickel cobalt aluminum oxide with a graphite electrode
NG	natural gas
NHTSA	National Highway Traffic Safety Administration
NMC	nickel manganese cobalt oxide
NMC-G	lithium nickel manganese cobalt oxide with a graphite electrode
NMP	N-methyl-2-pyrrolidone
NPV	net present value
NREL	National Renewable Energy Laboratory
PAN	polyacrylonitrile
PC	polycarbonate
PE	polyethylene
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
RNG	renewable natural gas
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
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
s	second(s)
ton	short ton (2,000 lb)
tonne	metric ton (1,000 kg)
V	volt(s)
Wh	watt hour(s)

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EXECUTIVE SUMMARY

This study provides a comprehensive life cycle analysis (LCA), or cradle-to-grave (C2G) analysis, of the cost and greenhouse gas (GHG) emissions of a variety of vehicle-fuel pathways, the levelized cost of driving (LCD) and cost of avoided GHG emissions. The C2G analysis assesses **light duty midsize sedans and small sport utility vehicles (SUVs) across a variety of vehicle-fuel technology pathways,** including conventional internal combustion engine vehicles (ICEVs), flexible hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) with varying vehicle ranges, and fuel cell electric vehicles (FCEVs).

Coming at a timely manner, given the marked increase, since 2016, in climate aspirations announced by governmental institutions and private firms both in the US and across the globe, this analysis builds on a previous comprehensive life cycle analysis, updating that study's 2016 assumptions and methods (Elgowainy et al. 2016). These updates incorporate technological advances and changes in energy supply sources that have emerged during the intervening period. Utilizing these updated assumptions and methods, alongside more recent data, the present report accounts for a broader range of vehicle technologies and considers both current (2020) and expected future (2030-2035) conditions. Reflecting increased research interest in synthetic liquid fuels produced using renewable low-carbon electricity and CO_2 sources, electro-fuels (a.k.a. e-fuels) were added to the potential future fuel technologies that are evaluated.

This study takes a "pathway" approach rather than a "scenario" approach; hence distinct, technically feasible, routes or sequences of processes starting with one or more feedstocks and ending with an intermediate or a final product are examined, not necessarily constrained by practical feedstock, economic, policy, and market considerations.

The fuel pathways considered in this study are shown in Table ES-1. The selected fuel pathways were 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 2035 U.S. grid generation mix projected by the U.S. Energy Information Administration (EIA) in the Annual Energy Outlook (AEO) 2021 (EIA 2021a).

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 (2020 version) with inputs from industrial experts. This C2G GHG assessment includes both fuel and vehicle production life cycles. Cost assessments represent a final cost/price to the consumer, excluding taxes on the final product (e.g., fuel sales tax) and/or credits (e.g., vehicle subsidies). Cost estimates for both vehicles and fuels are based on high-volume production ("at/above optimal scale"), the definition of which is intentionally not standardized across vehicle-fuel pathways, since scale is recognized as inherently a function of the technology/production pathway.

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)
		E-fuels (Nuclear electricity + CO_2)
		E-fuels (Renewable electricity + CO_2)
Diesel	U.S. average crude mix	Bio-renewable diesel (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)
		E-fuels (Nuclear electricity + CO_2)
		E-fuels (Renewable electricity + CO_2)
CNG	U.S. average of conventional and shale gas mix	Renewable natural gas (NG) (from landfill gas)
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)	Low temperature electrolysis from wind/solar
		High-temperature electrolysis using nuclear energy
		NG SMR with carbon capture and storage (CCS)
Electricity	EIA-AEO U.S. average electricity generation mix in 2020	NG Advanced Combined Cycle (ACC)
		NG ACC with CCS
		Wind
		Solar photovoltaic (PV)

[a] American Society for Testing and Material (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) is a biodiesel blend available in the U.S. that represents the maximum allowable concentration of biodiesel in ASTM D7467. FAME is also known as biodiesel. Percentage blending values are by volume.

The framework used in this study intentionally omits policy interventions to address technology or market challenges or opportunities. Costs are reported in 2020$ using the U.S. Bureau of Labor Statistics Consumer Price Index Inflation Calculator to convert costs to consistent 2020 dollars (BLS). Levelized cost estimates are based on financial inputs, technology parameters, and operational parameters, such as the price of energy feedstock, the capital cost of technology, process efficiency, capacity utilization, and operations and maintenance costs.

For transportation fuels currently at large-scale production levels—gasoline, diesel, CNG, corn-based ethanol (E85), and electricity—current and future fuel cost estimates come from the EIA AEO 2021 (EIA 2021). 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. For example, 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 (DOE H2A Production Analysis, 2015; Elgowainy et al. 2015).

The electricity mix used in stationary processes in FUTURE TECHNOLOGY pathways (unless otherwise specified) comes from the 2035 U.S. grid generation mix projected by the EIA in the AEO 2021 (EIA 2021a). The CURRENT TECHNOLOGY case assumes the AEO 2021 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 2021 estimates of the levelized cost of electricity from new generation resources. For electricity to EVs, this includes estimates for solar electricity and wind electricity which includes a "Green Premium", and electricity from ACC generation with and without CCS, which utilizes AEO 2021 and modified analysis from EIA AEO 215. Electricity for the other FUTURE TECHNOLOGY case pathways is based on the AEO 2021 projected average grid mix for 2035.

Vehicle fuel economies (see Section 6) and component sizes were estimated using Argonne National Laboratory's vehicle simulation tool, 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 assumptions made by the authors along with specific technology assumptions provided by DOE VTO-HFTO, which reflect vehicle performance improvements that are in line with targets set by these DOE offices for advanced vehicles. All vehicle platforms were evaluated using standard EPA regulatory drive cycles, UDDS and HWFET. Vehicles modeled in Autonomie met the following criteria: (1) vehicle acceleration from 0 to 60 mph in 8 s (±0.1 s), (2) gradeability of 6% at 65 mph at gross vehicle weight (GVW), and (3) maximum vehicle speed ≥100 mph.

The component sizes and vehicle fuel economy results were incorporated into the GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model suite (2021 version) to evaluate GHG emissions of vehicle production ("GREET2" model) and fuel cycles ("GREET1" model), respectively. Meanwhile, a range of future vehicle cost estimates (with vehicles modeled in 5-year time steps) were developed based on a range of technology progress (more optimistic and less optimistic), resulting in a low- to high-cost range, and these vehicle costs were used to evaluate the LCD.

The main case presented in this Executive Summary and in the body of the report is the *high powertrain technology* progression pathway with the *central cost* cases for each fuel. The ranges presented in the cost analyses include the low technology progression vehicle coupled with the high fuel cost (when available, and the central case when not), and the low range is the high technology progress with the lowest fuel cost (when available).

By far the largest and the most consequential change in the input assumptions between the 2016 study and this current update is in battery costs for BEVs. The past 5-10 years have seen dramatic reductions in the cost of EV batteries while, similarly, battery cost projections have also changed significantly over the past 5 years. It is hard to overstate the importance of the improvements in battery costs on this analysis.

Figure ES-1, below, represents a sub-set of the study results. The figure demonstrates that for the gasoline ICEV small SUV pathway, potential vehicle efficiency gains would bring emissions down from 429 g CO_2e/mi (indicated by the black line, which represents CURRENT TECHNOLOGY) to 322 g CO_2e/mi (indicated by the red line, which shows GHG emissions reductions in a FUTURE TECHNOLOGY case resulting from such potential future vehicle efficiency gains as higher powertrain efficiency); these emissions could be further reduced using a low-carbon fuel to between 91 and 52 g CO_2e/mi as represented by the endpoint of the grey arrows. We further see that the burden of vehicle production (indicated by the blue line, which represents the case in which the vehicle is operated on a 0 g CO_2e/mi fuel) for the ICEV accounts for 40 g CO_2e/mi of the FUTURE TECHNOLOGY emissions. Note that these vehicle production emissions do not include potential emissions reduction technologies for vehicle material production (these are considered in Appendix C). DOE and industry are pursuing technologies that reduce GHG emissions from the manufacturing sector, so it is expected that vehicle production emissions will decrease over time.

Figure ES-1 shows 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 from low-carbon fuels and electricity, but the feasibility of achieving the indicated GHG emission reductions were not considered. More broadly, these results demonstrate that large GHG reductions for LDVs are challenging and require consideration of the entire life cycle, including vehicle manufacture, fuel production, and vehicle operation. Achieving a net life cycle reduction in GHG emissions is a challenging task and must overcome technological, cost, and market acceptance hurdles.

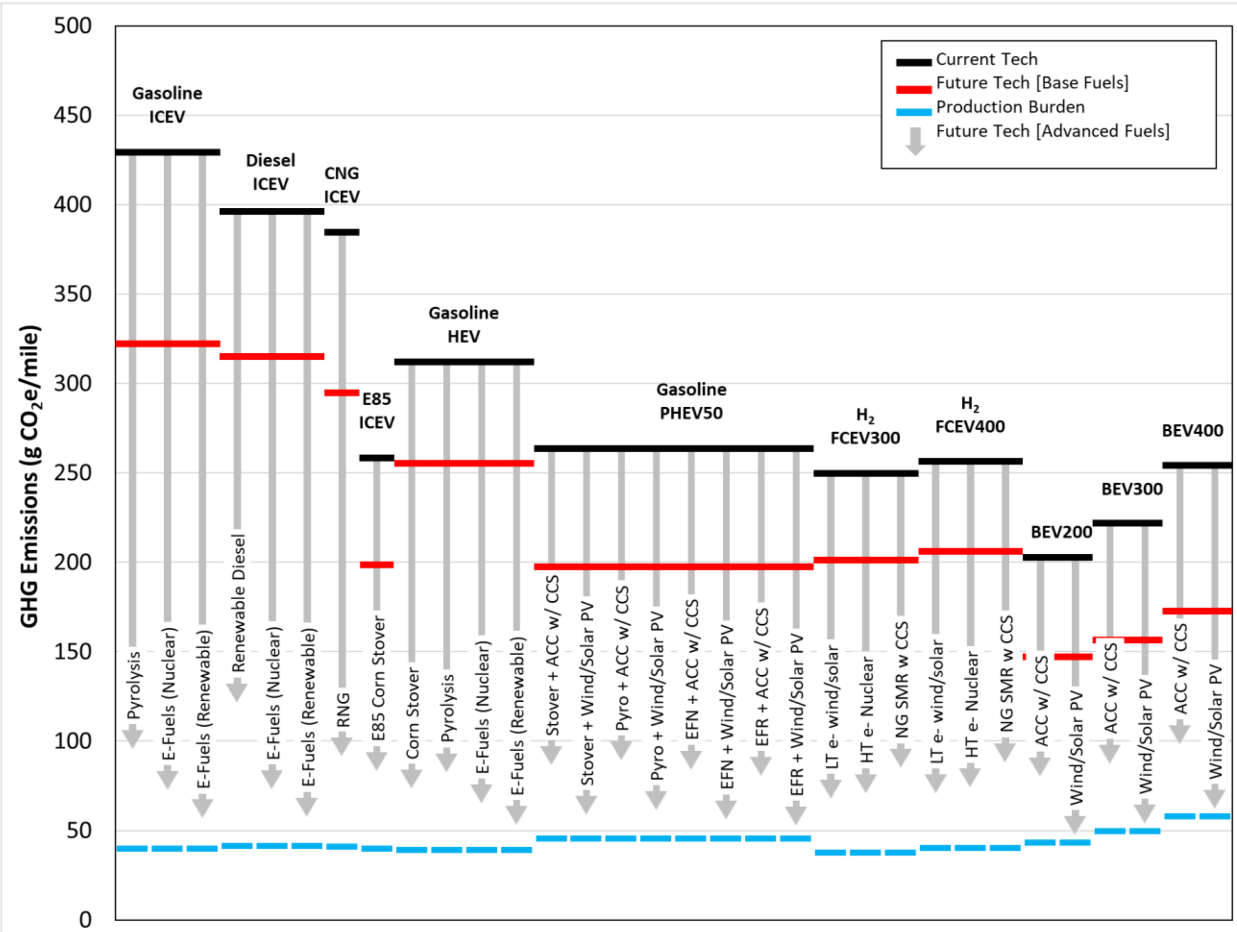

Figure ES-1. C2G GHG emissions of various vehicle-fuel pathways for small SUVs assuming high technology progress. Analysis was performed using GREET2020.

To better understand ownership costs of the vehicle-fuel platforms relative to one another and relative to gasoline ICEV baseline, Figures ES-2 and ES-3 show the LCD estimates 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 results shown are for the midsize sedan, using a base case vehicle and fuel costs over a 5-year analysis period using a 5%

discount rate. The uncertainty bars in Figure ES-3 reflect the range of LCD results for each vehicle-fuel pathway if low and high estimates are used for the vehicle and fuel costs.

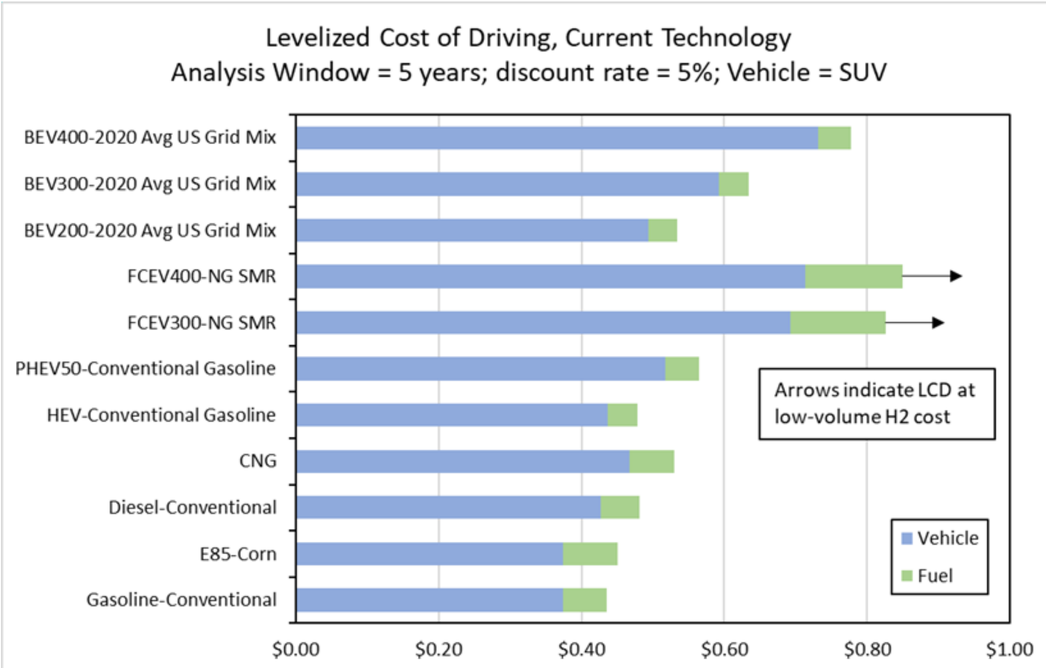

Figure ES-2. LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY small SUV (2020$)

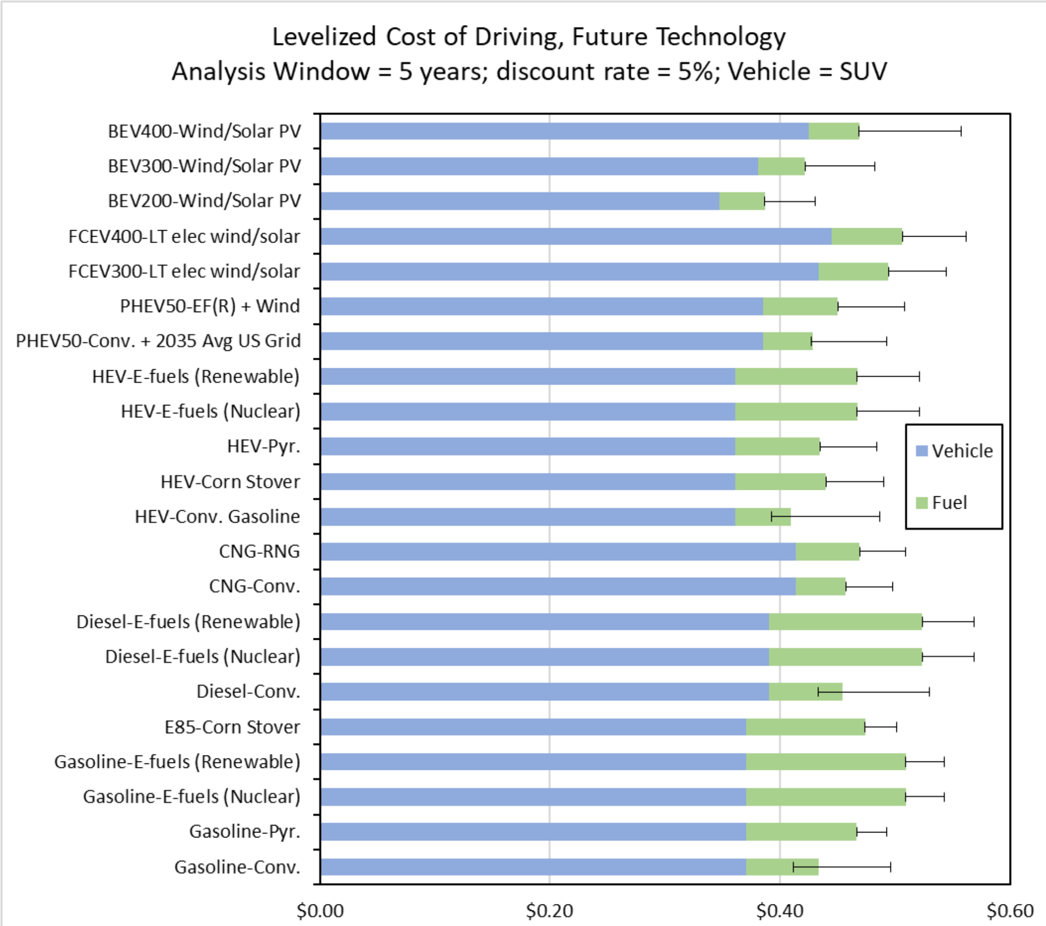

Figure ES-3. LCD by vehicle-fuel pathway for FUTURE TECHNOLOGY, small SUVs (2020$)

As seen in these two figures, for all vehicle-fuel pathways, the vehicle cost (less residual value) represents a significant portion of the total LCD. For the CURRENT TECHNOLOGY case, the more commercially established vehicles (gasoline, diesel, E85, and HEV) have LCDs below $0.50/mi for small SUVs. Emerging vehicle technologies, such as BEVs, PHEVs, and FCEVs for small SUVs have LCDs exceeding $0.55/mi**.** As shown in Figure ES-3, the FUTURE TECHNOLOGY case, improvements in technology and cost suggest that most vehicles will be below $0.50/mi in the baseline conditions for small SUVs, with BEVs demonstrating the largest cost reductions.

For the FCEV a CURRENT TECHNOLOGY low-volume hydrogen fuel cost estimate was developed for hydrogen fuel to better understand the impact of hydrogen fuel cost in the near term, shown as a black arrow in Figure ES-2. For FCEVs in the CURRENT TECHNOLOGY case, the low-volume cost of hydrogen increases the small SUV FCEV LCD from $0.85/mi to $0.93/mi, depending on the range.

Note that the cost analysis here does not provide a quantitative estimate of potential maintenance cost savings. However, other studies suggest that light-duty BEVs reduce maintenance costs compared to ICEVs by approximately 40% (Burnham, et al. 2021).

To allow for comparison of cost-effectiveness of potential emissions reductions across different strategies for GHG mitigation, a "cost of avoided GHG emissions" analysis is used. This analysis presents the total CO_2e emitted and total cost during the vehicle lifetime as a point on a two-dimensional plot. Additionally, the percent reduction in CO_2e from the gasoline ICEV is also presented.

The cost of avoided GHG emissions for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases for small SUVs are shown in Figures ES-4 and ES-5. Total emissions, over the noted time frame, are shown on the primary x-axis, and percent reduction from the conventional gasoline vehicle on the secondary x-axis, while lifetime vehicle cost is shown on the y-axis. The results indicate opportunities for GHG reduction with all powertrains. While cost reductions are not observed for the CURRENT TECHNOLOGY case, we find that several FUTURE TECHNOLOGY cases offer both cost and emission reduction opportunities.

The modeled costs of avoided GHG emissions for the majority of FUTURE TECHNOLOGY cases, considering the full 15-year vehicle lifetime, are below \$200/tonne CO_2e with many options below zero (i.e., they cost less than the ICEV and emit fewer emissions). Additionally, the BEV400 and FCEV pathways are markedly different from the CURRENT TECHNOLOGY case. The cost of those technologies, though still a major component of overall vehicle cost, is modeled to improve significantly over the intervening period, leading to a much lower total vehicle cost.

For the FUTURE TECHNOLOGY case, HEV, PHEV, and BEV platforms offer the lowest modeled costs of avoided GHG emissions, with many options having a negative cost (i.e., the cost is less than that of the gasoline ICEV). The FCEVs offer lower cost GHG emissions opportunities than the ICEV technologies with the exception of the E85 vehicle operating on corn stover and the CNG vehicle operating on RNG.

The vehicle technologies considered in this analysis differ, of course, not only in their lifetime GHG emissions but also in other important attributes, such as local air quality-related emissions, reliance on different fuels, functionality, and scalability. 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.

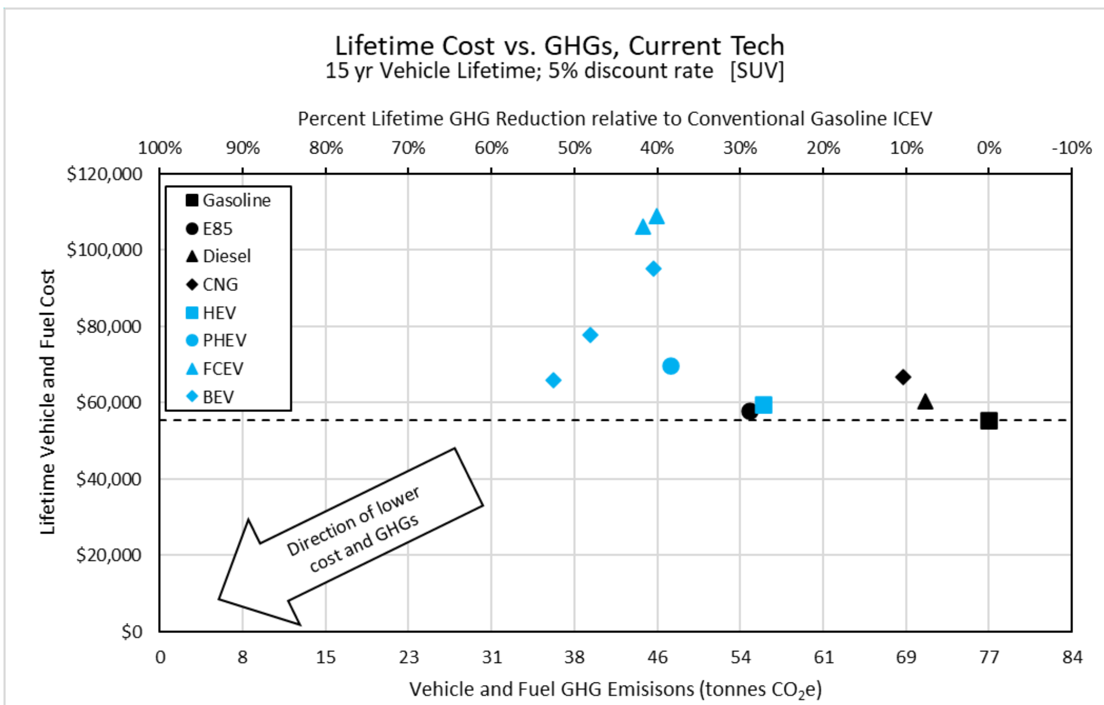

Figure ES-4. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY case for small SUVs (2020\$)

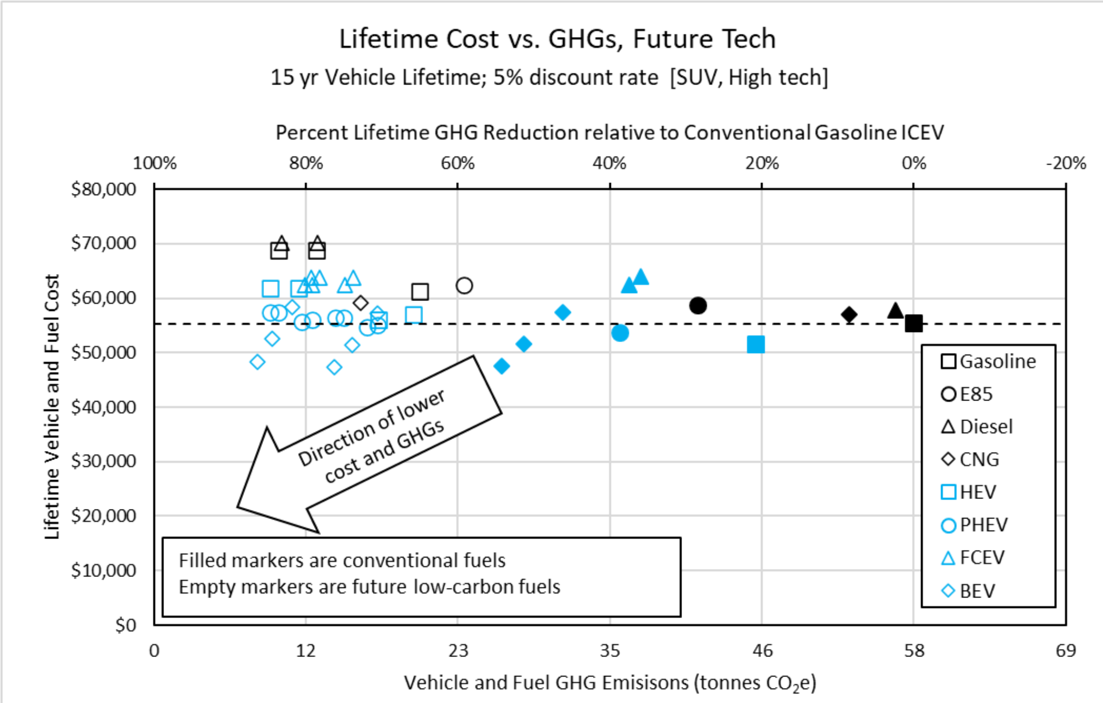

Figure ES-5. Lifetime cost versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY case for small SUVs (2020$)

The following observations are drawn from this report:

Emissions:

- Large GHG reductions for LDVs are achievable through low-carbon fuel pathways, with vehicle efficiency improvements also playing an important role.

Cost:

- FUTURE TECHNOLOGY costs for advanced technologies reduce faster than incumbent technologies compared to their CURRENT TECHNOLOGY counterparts, 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. 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.
- Several vehicles (HEV, PHEV, and BEVs) in the FUTURE TECHNOLOGY case had lower costs *and* lower GHG emissions than the conventional gasoline ICEV.

Cost of carbon abatement:

- For the CURRENT TECHNOLOGY 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 carbon abatement costs vary significantly by technology and fuel pathway, with several pathways, mostly electric vehicle, that are below zero (i.e., there is a cost reduction for carbon abatement). The pathways that do have a carbon abatement cost are generally 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 2021 data for prices of crude oil, gasoline, and diesel fuel used in the CURRENT TECHNOLOGY case differ from subject data reported for early 2022. 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 2022 prices were used. One of the consequences of using AEO 2021 data for the CURRENT TECHNOLOGY cases is that the prices of crude oil, gasoline, and diesel fuel used in this report are lower than actual market prices for those products in the first quarter of 2022 (the time this report was written).
- 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 dependence on technology advancement for the FUTURE TECHNOLOGY case. Furthermore, market scenario analysis is important to explore the realistic ramp up 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

This study builds on our previous life cycle analysis (LCA) of greenhouse gas (GHG) emissions and costs of light-duty midsize sedans for a variety of vehicle-fuel pathways (Elgowainy et al. 2016). We update the 2016 assumptions and methods to consider both current (2020) and expected future (2030-2035) conditions. This approach to LCA, often referred to as a cradle-to-grave (C2G) analysis, considers vehicle and fuel cycles starting from raw material extraction as well as fuel production and transport, vehicle manufacturing, vehicle use, and vehicle end-of-life (EOL), but not supporting infrastructure systems (e.g., refineries end-of-life or LCA of roads and bridges). A C2G analysis provides a holistic view of the sustainability performance of vehicle-fuel technologies across multiple metrics. This evaluation is intended to provide a thorough and up-to-date understanding of the sustainability performance of vehicle technologies and fuels to inform policymaking, investments, and analyses.

1.1. CLIMATE AND POLICY CONTEXT

Energy access and security, climate change, greenhouse gas (GHG) emissions, and water use are important long-term challenges for industry and governments. The U.S. transportation sector consumed 24.3 quadrillion Btu of primary energy sources in 2020, representing 35% of the total national energy consumption (EIA 2021d, Tables 1.3 and 2.1-2.6). In 2020, petroleum supplied 90% of U.S. transportation energy consumption. In marked contrast to 2016, when the U.S. was a major net *importer* of petroleum, the U.S. was a net *exporter* of petroleum in 2020 (EIA 2021d, Tables 2.5 and 3.3). GHG emissions attributed to the U.S. transportation sector in 2020 were 1.6 billion metric tons (tonnes) of CO_2-equivalent (CO_2e), representing 36% of the total national GHG emissions (EIA 2021d, Tables 11.1-11.6).

It is well established that the changes in global climate observed over the past 50-100 years are largely attributed to increasing levels of GHGs in the Earth's atmosphere resulting from human activities (Masson-Delmotte, et al. 2021). The largest contributor of radiative forcing is the release of CO_2 during fossil fuel combustion (Masson-Delmotte, et al. 2021). Light-duty vehicles (LDVs), the focus of this study, were responsible for approximately 58% of GHG emissions from the U.S. transportation sector in 2019 (EPA 2021). The U.S. Department of Energy (DOE) has supported substantial research, development, and demonstration of vehicle and fuel technologies to improve energy efficiency and reduce GHG emissions in the transportation sector. Advanced vehicle technologies include more efficient internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). Advanced fuel technologies include advanced biofuels, renewable electricity, and hydrogen.

Since our 2016 report, there has been a marked increase in the scope of climate aspirations announced by governmental institutions and private firms, with many organizations adopting carbon neutrality goals by 2040-2050. The U.S. rejoined the Paris Agreement in 2021 and submitted an Intended Nationally Determined Contribution to the United Nations, which outlines the economy-wide target of reducing GHG emissions by 26–28% below its 2005 level by 2025, and to make best efforts to reduce its emissions by 28%. The Biden Administration has set ambitious federal climate targets: a 50–52% reduction in economy-wide net GHG emissions from 2005 levels by 2030, 100% carbon-free electricity by 2035, and a 50% light-duty zero-emission vehicle sales share in 2030 (White House 2021a; White House 2021b). California passed the Global Warming Solutions Act of 2006 with a goal of reducing GHG emissions to 1990 levels by 2020, which it met in 2016. California aims to achieve a 40% reduction in GHG emissions below 1990 levels by 2030 and carbon neutrality by 2045. The European Union set goals of a

55% reduction in GHG emissions by 2030 from a 1990 baseline and carbon neutrality by 2050, with many countries aiming to achieve the goal earlier. China has committed to carbon neutrality by 2060.

Large reductions in emissions from the transportation sector will be needed to meet national and state climate targets, and reductions of LDV emissions will play a major role in achieving these goals. The adoption of zero-emission LDVs has increased exponentially in the past few years, highlighting the potential for a major emissions reduction in the next decade (Muratori et al. 2021; IEA 2021). However, zero-emission vehicles (ZEV) remain a small share of U.S. LDV sales (~5% in 2021). Technological assessments of life cycle GHG emissions and costs for different vehicle-fuel combinations are critical for informing near and long-term actions and policy decisions. The aim of the present work is to analyze such emissions and costs in the context of U.S. LDVs in the present (2020) and future (2030-2035).

1.2. PREVIOUS LCA AND C2G WORK

Previous LCAs of energy use and GHG emissions from LDVs in the U.S. have focused on 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, onboard 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.

LCAs of conventional petroleum-powered ICEVs show that approximately 80% of WTW GHG emissions and energy use are associated with fuel combustion during vehicle operation (Elgowainy et al. 2014, 2016). In advanced vehicle technologies, the amount of fuel used by the vehicle is typically less than that of ICEVs, but the energy used to produce the vehicle is greater. Thus, for advanced vehicle technologies, it is important to also consider the emissions and energy use associated with the vehicle manufacturing cycle. Combining the vehicle and fuel cycle analyses produces a C2G assessment that encompasses resource extraction ("cradle"), transformation of resources into fuels and vehicles, and fuel use in vehicle operation and vehicle EOL scrappage and recycling ("grave"). The boundary here does not include the construction or EOL of infrastructure systems that support the vehicles or energy pathways. The carbon footprint for energy infrastructure is typically trivial compared to energy generated/handled by the infrastructure as documented by Beath et al. 2014 for U.S. oil and gas production and processing.

In 2014, the DOE published a C2G analysis that was comprised of 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 (in this case 2010), such as gasoline-ICEVs, E85[1] 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 low-carbon world. The C2G results were produced with Argonne's Greenhouse gas, Regulated Emissions, and Energy use in Technologies (GREET®) model (version 2014) with inputs that were vetted by experts from other national laboratories and from the energy and auto industries.

In 2016, Elgowainy et al. updated the model assumptions, expanded the scope of the initial DOE study (Joseck and Ward 2014), and documented the results in two publications (Elgowainy et al. 2016; 2018).

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

In the period following the 2016 study, there were substantial technological advances and changes in energy supply sources, particularly in vehicle electrification and renewable electricity generation, which warrant an update of the previous work. In the present study, we updated and expanded the analysis to a broader range of vehicle technologies that now includes small SUVs, BEVs with 400-mile range (BEV400), and PHEVs with 50-mile all-electric range (PHEV50). We also evaluated electro-fuels (a.k.a. e-fuels) as a potential future fuel technology to reflect increased research interest in synthetic liquid fuels produced using renewable low-carbon electricity and CO_2 sources.

1.3. OVERVIEW OF THE PRESENT C2G STUDY

The present study assesses future vehicle-fuel pathways that are similar, but not identical, to those in the previous study. As in the previous study we assess GHG emissions and costs of the pathways.

This C2G study focuses on the LDV market, particularly the midsize sedan and small SUV segments, and evaluates a variety of conventional and alternative vehicle technologies and fuels. In evaluating the vehicle-fuel combinations, we consider a "CURRENT TECHNOLOGY" case (nominally 2020) and a "FUTURE TECHNOLOGY" lower-carbon case (nominally 2030–2035).[2] We use a "pathway" 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 final product. A pathway is not necessarily constrained by practical feedstocks or economic, policy, and market considerations. This approach contrasts with the definition of a scenario, which is a postulated vehicle-fuel production pathway or a mix of pathways that factors in real or hypothetical/perceived feedstocks and economic, policy, and market considerations. This study focuses strictly on possible vehicle-fuel combination pathways (i.e., no scenario analysis was conducted).

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 FCEVs and BEVs, were not considered. Unless otherwise specified, all cases assume large-scale production for both fuel and vehicle technologies (i.e., high production volume is assumed unless explicitly specified). The electricity mix used in the stationary processes in the FUTURE TECHNOLOGY pathways comes from the 2035 U.S. grid generation mix projected by the U.S. Energy Information Administration (EIA) in the Annual Energy Outlook (AEO) 2021 (unless otherwise specified) (EIA 2021a).

2 Throughout this report, the cases studied will be denoted in a Small Caps typeface for consistency and clarity.

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)
		E-fuels (Nuclear electricity + CO_2)
		E-fuels (Renewable electricity + CO_2)
Diesel	U.S. average crude mix	Bio-renewable diesel (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)
		E-fuels (Nuclear electricity + CO_2)
		E-fuels (Renewable electricity + CO_2)
CNG	U.S. average of conventional and shale gas mix	Renewable natural gas (NG) (from landfill gas)
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)	Low temperature electrolysis from wind/solar
		High-temperature electrolysis using nuclear energy
		NG SMR with carbon capture and storage (CCS)
Electricity	EIA-AEO U.S. average electricity generation mix in 2020	NG Advanced Combined Cycle (ACC)
		NG ACC with CCS
		Wind
		Solar photovoltaic (PV)

[a] American Society for Testing and Material (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) is a biodiesel blend available in the U.S. that represents the maximum allowable concentration of biodiesel in ASTM D7467. FAME is also known as biodiesel. Percentage blending values are by volume.

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 PHEV50, BEV200, BEV300, and BEV400 technologies are defined to have 50, 200, 300, and 400 miles of range, respectively, from a single full charge in real-world driving. The PHEV50 was modeled as an extended-range electric vehicle (EREV) (Islam et al. 2021). 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 the 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	E-Fuels	E85[b]	H_2	Electricity
ICEV	X	X	X	X	X	–	–
HEV	X	–	–	–	–	–	–
H_2 FCEV300[c]	–	–	–	–	–	X	–
H_2 FCEV400[d]	–	–	–	–	–	X	–
BEV200[e]	–	–	–	–	–	–	X
BEV300[f]	–	–	–	–	–	–	X
BEV400[g]	–	–	–	–	–	–	X
PHEV50 (EREV)[h]	30%[i]	–	–	–	–	–	70%[i]

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

[b] Blend of ethanol fuel grade with gasoline, as explained in footnote 1.

[c] H_2 FCEV300 has a 300-mi "on-road" driving range.

[d] H_2 FCEV400 has a 400-mi "on road" driving range.

[e] BEV200 has a 200-mi "on road" driving range.

[f] BEV300 has a 300-mi "on road" driving range.

[g] BEV400 has a 400-mi "on road" driving range.

[h] PHEV35 has a 50-mi "on road" electric range and is modeled as an EREV.

[i] The fraction of total miles driven on fuel or electricity is assumed per the Society for Automotive Engineers International (2010). The exact fraction for the nominal PHEV50 depends on its on-road range, as described in Section 3.2.

1.4. Report Organization

The remainder of this report is organized into 11 sections (2–12) and 5 appendices (A–E). Section 2 provides an overview of the methodology for modeling fuel pathways and vehicle technologies. Section 3 describes the selected vehicle technologies 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 life cycle 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 study for consideration in future studies. Section 12 provides brief conclusions about this work.

Appendix A compares vehicles modeled in this report with vehicle sales data. Appendix B provides more detailed GHG emissions results. Appendix C analyzes the sensitivity of GHG emission to key parameters. Appendix D provides parameters and results for the low powertrain technology progression scenarios. Appendix E provides example calculations of the LCD to clarify how these costs were developed. Finally, Appendix F compiles all the references used in this study by aggregating the references provided at the end of each section.

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2. OVERVIEW OF METHODOLOGY

This study is intended to provide a better understanding of the GHG emissions and costs associated with the vehicle and fuel combinations described in (Elgowainy et al. 2016). Note that in this context cost represents the cost to a consumer to purchase the vehicle and energy for the vehicle; it does not include maintenance, insurance, and other costs necessary in vehicle ownership. There are numerous vehicle-fuel combinations considered in this analysis, thus a consistent set of parameters and a common analytical framework was employed to allow comparative evaluations. This section provides an overview of the data, assumptions, and analytical framework used in this study.

2.1. STUDY SCOPE, DEFINITIONS, AND MAJOR ASSUMPTIONS

This study focuses on the LDV sector in the U.S. Specifically, it focuses on vehicle models classified as midsize sedans (such as the Honda Accord, Kia Optima, Mazda 6, and Volkswagen Passat) and small SUVs (such as the Chevrolet Equinox, Ford Escape, Mazda CX-5, and Toyota RAV4). While the results for different vehicle classes (e.g., compact cars or large SUVs) will differ from these results, general trends from the midsize and small SUV evaluations should provide directional insights and deepen life cycle understanding across vehicle classes.

Table 1 and Table 2 outline the vehicle and fuel technologies considered in this analysis, which include ICEVs, HEVs, PHEVs, BEVs, and FCEVs utilizing several different fuel (energy) pathways.

The C2G analysis contains two primary evaluations: an evaluation of the life cycle GHG emissions associated with each vehicle-fuel combination, and a determination of the associated driving costs for each combination. Within the respective vehicle classes, this evaluation utilizes a consistent vehicle platform with equivalent performance parameters for both conventional and alternative powertrain platforms. Those vehicle properties, as described in Section 6, are developed using the Argonne National Laboratory vehicle system simulation tool, Autonomie, with support from the DOE (Islam et. al., 2021). The outputs of those vehicle simulations provided vehicle characteristics, such as vehicle fuel economy, component costs, and component weights. The analysis also utilizes evaluations and cost modeling of fuel technologies.

This analysis treats “cost” as a policy-neutral final transaction cost. Thus, costs are the final cost/price to the consumer, excluding taxes on the final product (e.g., fuel sales tax) and/or credits (e.g., vehicle subsidies). The framework intentionally omits policy interventions to address technology or market challenges or opportunities. In this report, costs are reported in 2020$ using the U.S. Bureau of Labor Statistics Consumer Price Index Inflation Calculator to convert costs to consistent 2020$ (U.S. Bureau of Labor Statistics 2021.

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 an inherent 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, was modeled to represent the vehicle model year (MY) 2020 and to characterize fuel production technologies available in 2020, with costs projected at high volume. A sensitivity low-volume case was evaluated for the production and distribution of current hydrogen. The FUTURE TECHNOLOGY case represents MY2030–2035 vehicles and fuels projected at high volume for all vehicle and fuel technologies.

Though the study does consider low-volume costs in some instances, the primary evaluation is of vehicles and fuels at high-volume production, 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 GHG EMISSIONS LCA

The research approach of this analysis closely follows the methodology used in the 2016 C2G study (Elgowainy et al. 2016). As this text builds upon and updates that report, no distinction is made between that original text and updates within this report.

In assessing life cycle emissions, this study considers emissions associated with the fuel and the vehicle cycle. The C2G GHG emissions assessment was carried out by expanding and modifying the GREET model suite with inputs from industrial experts[3]. Figure 1 shows the main life cycle stages covered by the fuel cycle model (GREET1) and the vehicle cycle model (GREET2). The GREET1 model calculates the energy use and emissions associated with the 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 more than 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 the 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. The model does not include the energy use and emissions from the transportation of raw and processed materials for each process step. 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 U.S.

3 This analysis uses the GREET 2020 release from Argonne National Laboratory (Wang 2020a).

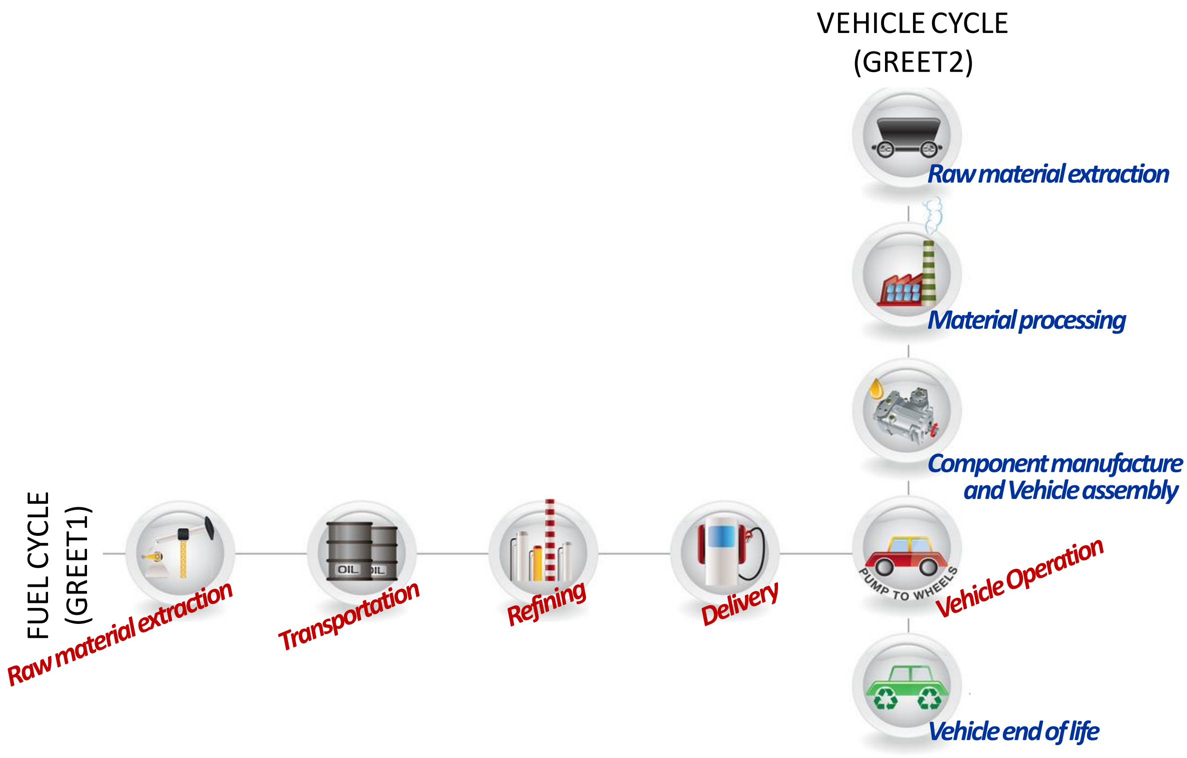

Figure 1. Combined fuel cycle and vehicle cycle activities included in C2G analysis

The first step in the vehicle-cycle analysis is to estimate the 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[4], body interior, body exterior, and glass), chassis, batteries, fluids, powertrain (e.g., a spark-ignition (SI) engine or a fuel cell stack and auxiliaries), and transmission or gearbox. The detailed weights of vehicle components weight are provided by Autonomie simulations. Depending on the vehicle type, the component weight could include the weight of a motor, controller, and generator. The second step in the vehicle-cycle model is to consider the material composition for each major vehicle component (i.e., breakdown the 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 the 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

As in our prior analysis, the evaluation of vehicle technologies is conducted using publicly available data and models. Vehicle fuel economies and component sizes are estimated using Autonomie, with a consistent set of vehicle performance criteria across fuel-vehicle combinations. Each vehicle is presumed

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

to be optimized for the fuel on which it operates. Inputs to Autonomie are based on vehicle manufacturer information and assumptions made by the authors, along with specific technology assumptions provided by DOE Vehicle Technologies Office (VTO) and Hydrogen Fuel Technology Office (HFTO); these inputs are detailed in Islam et al., (2021).

A full suite of vehicle powertrain technologies is considered for both the midsize sedans and small SUVs evaluated. This includes conventional ICEVs, HEVs, PHEVs, BEVs, and FCEVs, and the fuels that power them (petroleum, NG, ethanol, e-fuels, hydrogen, and electricity). These analyses only consider differences in fuel pathways and vehicle operation, not other potential confounding factors (e.g., aesthetic differences in vehicle design), and vehicles are modelled to have the same capability and performance. Vehicles are modeled with the presumption of a common vehicle "glider" coupled with specific components for each vehicle platform (transmission, engine/motor, energy storage/fuel tank, emission controls, etc.) and vehicle class (midsize sedan and small SUV).

Vehicle energy consumption is the most critical attribute in determining all other metrics of interest. In this study, vehicle efficiency is expressed as fuel economy. For the set of vehicles examined, fuel economies are expressed in gge terms and as a percentage of the baseline vehicle. The baseline midsize vehicle (SI ICEV) has an assumed fuel economy of 30.7 mpg, while the baseline small SUV (SI ICEV) has an assumed fuel economy of 27.5 for the CURRENT TECHNOLOGY case.[5] Fuel economy assumptions are based on scenario results from Autonomie, with all vehicle platforms evaluated using standard Environmental Protection Agency (EPA) regulatory drive cycles, Urban Dynamometer Driving Schedules (UDDS), and Highway Federal Emissions Tests (HWFET). The accurate Society for Automotive Engineers International (SAE) procedures for electrified vehicles (HEVs, PHEVs, and BEVs) are performed accordingly. Autonomie modeling reflects vehicle performance improvements in line with DOE VTO-HFTO targets for advanced vehicles. A range of future vehicle cost estimates from low to high are developed based on a range of technological progress (more optimistic and less optimistic). The base vehicle platform costs are based on the more optimistic progression in technology.

2.4. FUEL MODELING APPROACH

The fuels evaluated in this study are similar, but not identical, to those used in the 2016 study. They include conventional gasoline and diesel; NG-based fuels; biofuels, including ethanol, pyrolysis fuels, and various biodiesel fuels; hydrogen for FCEVs; and electricity produced from various pathways for BEVs and PHEVs. Specifically, feedstocks and fuel production pathways include:

- Corn and corn stover for E85
- Fast pyrolysis forest residue for renewable gasoline and diesel
- GTL FTD for diesel with and without CCS
- CNG and renewable NG (from landfill)
- Soybeans (soy oil to FAME)
- Electrolysis—NG reforming with CCS and woody biomass gasification—for hydrogen
- E-fuels for gasoline and diesel
- 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, which we define as capable of meeting 10% of fleet demand.

[5] Combined 43/57 UDDS-HWFET EPA two-cycle (adjusted) fuel economy. Note that the baseline ICEV uses a turbo-charged powertrain system.

As with the vehicle modeling, fuels investigated in this study are assessed based on publicly available data and models, and assumptions made by the authors. For transportation fuels currently at large-scale production levels (gasoline, diesel, CNG, corn-based ethanol (E85), and electricity) current and future fuel cost estimates come from the EIA AEO 2021(EIA 2021a). The CURRENT TECHNOLOGY case assumes the AEO 2021 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 Annual Energy Outlook 2021estimates of the levelized cost of electricity from new generation resources. For electricity to BEVs and PHEVs, this includes estimates for solar and wind electricity that include a "Green Premium", and electricity from ACC generation with and without CCS, which utilizes AEO 2021 and a modified analysis from EIA (EIA 2015). Electricity for the other FUTURE TECHNOLOGY case pathways is based on the AEO 2021 projected average grid mix for 2035.

For the remaining fuels (hydrogen, advanced biofuels, e-fuels), this study bases its cost assessment on publicly available data and models. The hydrogen fuel pathways and several of the bio-derived fuel pathways are 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 cost 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 use publicly available TEA models to generate fuel costs using a standard set of assumptions chosen specifically for this study. This approach ensures that fuel evaluations are consistent across fuel pathways. Common parameters for TEA models include 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 (pyrolysis and ethanol from corn stover) are evaluated using external models and reports, which are described in greater detail in Section 5.

Details on the data sources and models 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="6">Fuel Data Source</th></tr>
<tr><th>Gasoline</th><th>E85</th><th>Diesel</th><th>CNG</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">EIA AEO (and TEA models for FUTURE TECHNOLOGY pathways)</td><td rowspan="4"></td><td rowspan="2"></td></tr>
<tr><td>HEV</td><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="4"></td></tr>
<tr><td>PHEV</td><td rowspan="2">EIA AEO</td></tr>
<tr><td>BEV</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>FCEV</td><td></td><td></td></tr>
</table>

2.5. REFERENCES FOR SECTION 2

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3. VEHICLE-FUEL PATHWAY SELECTION AND VEHICLE TECHNOLOGIES

This analysis considers the coupling of multiple vehicle-fuel pathways with different vehicle technologies to estimate their associated costs and GHG emissions. This study does not investigate the technology readiness levels of either the vehicle technologies or the fuel pathways.

3.1. VEHICLE-FUEL PATHWAYS

A wide spectrum of LDV powertrains (conventional ICEVs, HEVs, PHEVs, BEVs, and FCEVs) and fuels (petroleum, CNG, ethanol, hydrogen, and electricity) for both midsize sedans and small SUVs are considered. Our primary intent is to understand energy use and emissions ranges for each vehicle-fuel combination and allow for comparisons across these combinations. In all cases, vehicles are presumed to be optimized for the fuel on which they operate. Table 2 shows the 12 vehicle-fuel combinations that are analyzed for each vehicle type.

Vehicles are assumed to be identical in size, shape, weight, capability, and performance within their respective vehicle class (except for changes to the powertrain) to ensure that the analysis results only reflect differences in fuel pathways and vehicle operation, rather than confounding factors. A consistent parameter set is chosen to compare a broad spectrum of powertrain types and fuel options. The baseline vehicle ("gasoline ICEV") is a typical midsize sedan or small SUV operating on conventional gasoline (E10) with a conventional SI turbocharged engine.

The fuel pathways considered are 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) are chosen to span the range of current mainstream offerings to low-carbon fuel cases in the future. The generation of electric power from wind and solar PV is assumed to be zero-carbon in the baseline scenario, meaning that this analysis may underrepresent GHG emissions by not accounting for those associated with infrastructure construction. This is methodologically consistent with other electricity generating assets in this analysis, but a recent system review of the literature indicates that the GHG emissions associated with wind and solar infrastructure have a median value of 13 g CO_2e/kWh and 43 g CO_2e/kWh, respectively (National Renewable Energy Laboratory 2021). A detailed description of vehicle technologies and fuel pathways is given in the following sections.

3.2. DESCRIPTION OF SELECTED VEHICLE TECHNOLOGIES

CURRENT TECHNOLOGY (MY2020) technologies are estimated based on recent state-of-the-art technology lab demonstrations. FUTURE TECHNOLOGY (MY2030–2035) estimates consider a range of possible technology pathways and explicitly recognize uncertainty (low being business-as-usual, high being DOE VTO-HFTO goals) in technological progress, as discussed in Section 6. It is important to emphasize that Autonomie models generic vehicles that employ 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 Islam et al. (2021).

This analysis includes four types of plug-in vehicles: BEVs with ranges of 200 mi (BEV200), 300 mi (BEV300), and 400 mi (BEV400), and PHEVs with a CD range of 50 mi (PHEV50). These vehicles are taken from Islam et al. (2021). 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 CD driving ranges indicated by the numbers following "BEV" and "PHEV." These values can refer to ranges measured on EPA Corporate Average Fuel Economy combined regulatory drive cycles of UDDS and HWFET, adjusted for real-world driving. Furthermore, they refer to ranges measured at the vehicle battery energy beginning-of-life (BOL). In this report, we 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) that are not accounted for in the EPA regulatory drive cycles, the real-world fuel economy achieved by modern vehicles is typically less than that measured in the EPA regulatory 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 regulatory drive cycles and procedures.

To avoid complications with estimates of battery deterioration over the vehicle lifespan, and for consistency with the marketplace, we quote BOL ranges. In the Autonomie report, BOL is used for all BEVs and PHEVs (Islam et al. 2021).

The breakdown of total miles driven on gasoline and electricity for the PHEV50 is calculated using the fleet utility factor coefficients in SAE (Society for Automotive Engineers International 2010). The calculated value is approximately 30% for gasoline and 70% for electricity and is assumed to be constant over the lifetime of the vehicle.

Vehicle fuel economies and component sizes are calculated 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 are based on vehicle manufacturer's information and Argonne assumptions. Vehicles modeled in Autonomie meet the following criteria: (1) vehicle acceleration from 0 to 60 mph in 8 s (±0.1 s), (2) gradeability of 6% at 65 mph at gross vehicle weight (GVW), and (3) maximum vehicle speed ≥100 mph.

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 and fuel cell technologies (PHEV50, BEV200, BEV300, BEV400, and H_2 FCEV) may still pose a market barrier in the near term.

3.3. References for Section 3

Islam, E. S., Vijayagopal, R., Kim, N., Moawad, A., Dupont, B., Nieto Prada, D., & Rousseau, A., 2021. *A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050* (ANL/ESD-21/10). Argonne National Laboratory.

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4. FUEL PATHWAYS: GHG ASSUMPTIONS AND DATA SOURCES

4.1. PETROLEUM PATHWAYS

The life cycle 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. In addition to 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 included. Infrastructure-related activities (e.g., construction of drilling rigs and petroleum refineries) have much smaller GHG emissions contributions compared to WTW GHG emissions per unit of fuel produced, and thus are not the focus of this study. Figure 2 shows the LCA system boundary and key stages and activities associated with the petroleum fuel pathway.

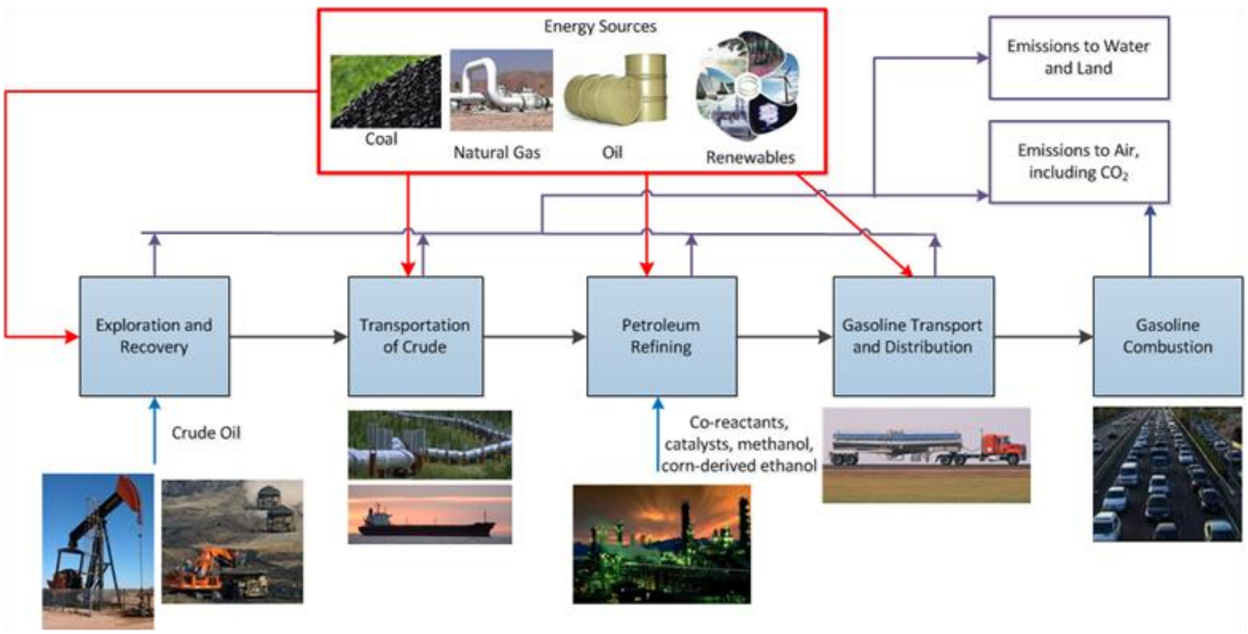

Figure 2. Key stages and activities of the petroleum fuels pathway (showing gasoline as an example) (figure originally appeared in Elgowainy, et al. 2016)

The petroleum recovery stage includes oil extraction and pretreatment. In some fields, associated gas is a byproduct of crude oil recovery that contains 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 time horizon) (Myhre et al. 2013). While the calculated energy efficiency for petroleum recovery does not account for the energy in the portion of gas flared or vented because it is not an intended energy product, the emissions associated with gas flaring and venting are taken into account in GREET life cycle emissions models.

In 2020, for the first time since 1949, the U.S. became a net petroleum exporter with domestic petroleum production and consumption averaging 18.4 and 18.1 million barrels per day, respectively (EIA 2021a). U.S. petroleum consumption, production, imports, exports, and net imports is covered in Table 3.1 (EIA 2021a). Argonne annually updates the regional shares of U.S. crude oil supply based on the AEO. In GREET 2020, the U.S. domestic crude oil production shares were updated based on the AEO projection

(EIA 2021a), while the crude oil import shares from Canada, Mexico, the Middle East, Latin America, and Africa were estimated using company-level import data (EIA 2020b). Further details on domestic shale oil production shares and the split between Canadian conventional crude and Canadian oil sands are provided in the Summary of Expansions and Updates in GREET® 2020 (Wang et al. 2020a).

4.1.1. Crude Production

Crude oil resources around the world vary significantly in quality and production methods, resulting in significant variation in GHG emission intensities associated with crude recovery (Masnadi et al. 2018). The 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 a detailed characterization of the energy intensities of 27 oil sands projects, representing industrial practices from 2008 to 2012 (Englander and Brandt 2014). Four major oil sands production pathways are 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 are considered separately to evaluate the impact of differences in oil sands production technologies and types of products on energy and emission intensities. Table 5 shows the energy consumption intensity for these four pathways, along with that for conventional crude (Cai et al. 2014).

Table 5. 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	Conventional Crude
Bitumen extraction and separation	0.080	0.080	0.20	0.20	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	–
Crude transportation	0.026	0.018	0.026	0.018	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. Vented, flaring, and fugitive (VFF) GHG emissions associated with crude oil production are based on 2018 GHG Emission Inventory (EPA 2018), with details provided in Ou and Cai (2018). Table 6 shows the VFF CH_4 and CO_2 emission factors from U.S. crude oil production in g/MMBtu of crude.

Table 6. VFF CH_4 and CO_2 emission factors from U.S. crude oil production (g/MMBtu of crude)

	CH_4	CO_2
VFF emission	80	1083

4.1.3. Crude Refining

Energy consumption by the refining industry in 2012 represented approximately 10% of the total energy supplied to U.S. refineries, with about 90% of the energy retained in the final refined products (EIA 2013). Elgowainy et al. used a linear programming model to conduct an in-depth analysis of 43 large U.S. refineries, each with a refining capacity greater than 100,000 bbl/day. Although the 43 refineries represent only 31% of the total 139 operating refineries in the U.S., they represent 70% of the total U.S. refining capacity and span a wide range of crude sources and qualities, product slates, and refinery complexities in different Petroleum Administration for Defense District 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), they 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 7 shows the details of process fuel use per unit fuel produced for major refinery fuel products based on Elgowainy et al. (2014). Depending on the crude slate fed to U.S. refineries each year, these energy intensities are adjusted in GREET based on average crude quality (i.e., American Petroleum Institute (API) gravity and sulfur content).

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). Vehicle fuel use and the associated GHG emissions are determined by the vehicle fuel economy (see Section 6).

Table 7. 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 NG in GREET and defined as "still gas."

4.2. NG Pathways

The life cycle of NG for use in CNG vehicles begins with 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 3 shows the WTW system boundary and key stages and activities associated with the CNG pathway.

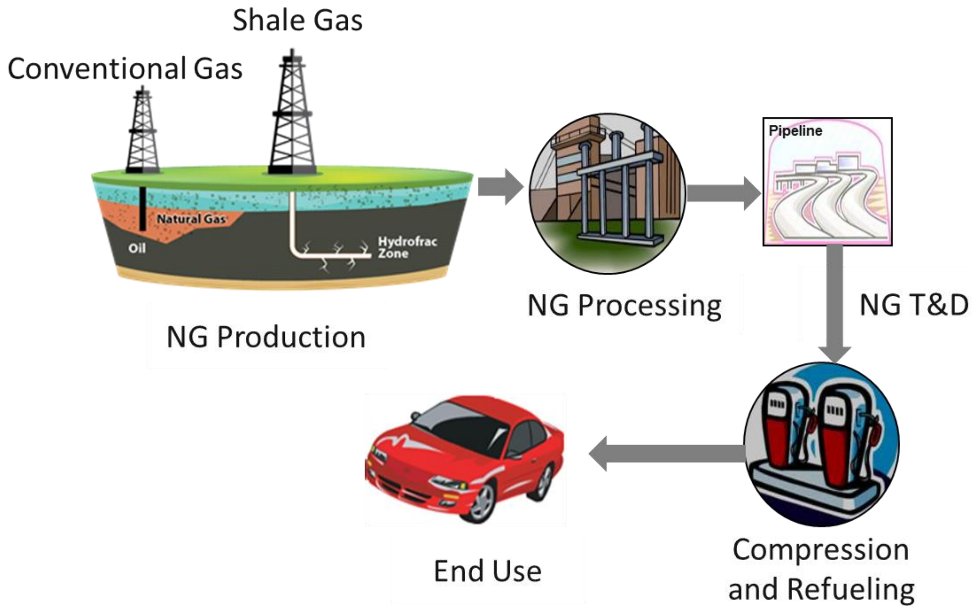

Figure 3. Key stages and activities of the CNG pathway (figure originally appeared in Elgowainy, et al. 2016)

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 its 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. Based on published data and previous inputs from energy companies, the energy efficiencies for both gas recovery and processing are assumed to be 97.2%, accounting for feedstock losses in the energy efficiency calculation (Brinkman et al. 2005), which translates to 97.5% and 97.4% for gas recovery and processing, respectively, if losses are not counted in the denominator of the energy efficiency calculations.

Burnham used CH_4 emissions data from the EPA 2020 GHG inventory (EPA 2020) to estimate the life cycle GHG emission impacts of various stages and activities of the NG pathway (2020). Several studies demonstrated shortcomings in the EPA CH_4 inventory, which has discrepancies with atmospheric measurements (top-down approach) of CH_4 emissions from gas fields. However, the EPA inventory remains the best publicly available data source for emissions from specific activities.

Table 8 summarizes CH_4 fugitive emissions for both shale and conventional gas in GREET based on the EPA inventory (2020). Table 9 shows the corresponding CH_4 leakage rate based on NG throughput by stage (Burnham 2020).

Table 8. Summary of CH_4 emission factors by activity in GREET 2020 (g CH_4/MMBtu NG) (Burnham 2020)

Sector	Process	Shale Gas	Conventional Gas
Production	Completion	4.82	0.530
	Workover	0.974	0.007
	Liquid unloading	5.03	5.034
	Well equipment	71.9	71.9
Processing	Processing	5.2	5.2
Transmission	Transmission and storage	38.7	38.7
Distribution	Distribution (station pathway)	16.7	16.7
Total		143.3	138.1

Table 9. CH_4 leakage rate based on NG throughput by stage (%)

Stage	Shale Gas (2020)	Conv. Gas (2020)
Gas field	0.40%	0.37%
Completion/workover	0.03%	0.0%
Unloading	0.02%	0.02%
Other sources	0.35%	0.35%
Processing	0.03%	0.03%
Transmission	0.19%	0.19%
Distribution	0.08%	0.08%
Total	0.70%	0.67%

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 biodiesel or FAME from soybeans. The life cycle of biofuels includes multiple elements, such as fertilizer production, farming, and conversion of feedstock to biofuel, all of which consume fossil energy and produce GHG emissions. According to DOE's BillionTon Report (2016), the total potential annual non-food, sustainable biomass resources available in the US by 2040 for energy products and co-products is at least 1 billion dry tons. Assuming a fuel production yield of 80 gal/dry ton, the annual potential capacity for annual biofuel production is in the order of 80 billion gal.

4.3.1. Corn Ethanol

Figure 4 shows the system boundary of the bio-ethanol pathway in the GREET model. Corn farming and ethanol production are the two major, direct GHG emission sources in the corn ethanol pathway. In the farming stage, N_2O emissions from the nitrification and denitrification of nitrogen fertilizer in cornfields is a major GHG emissions source. NG 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.

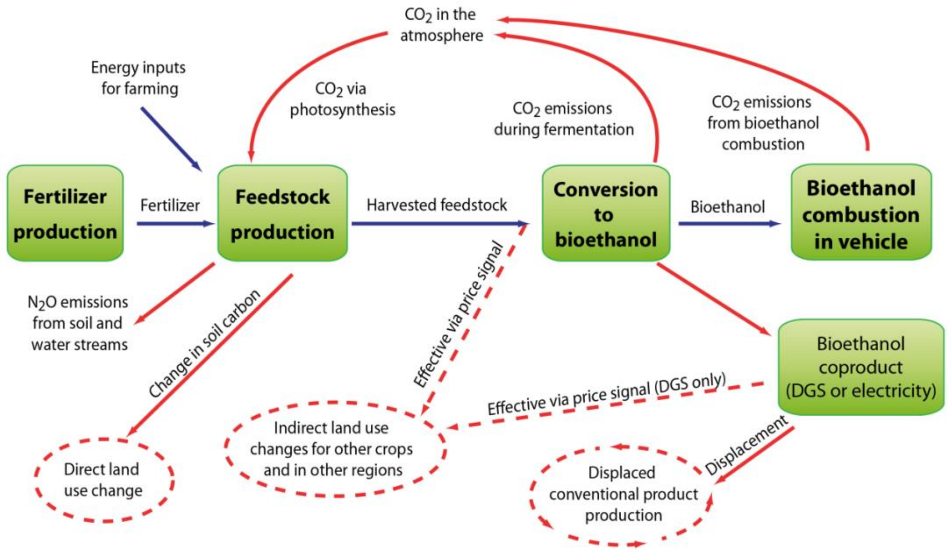

Figure 4. Bio-ethanol pathway activities in GREET

In GREET 2020, ethanol yield with and without corn extraction is assumed to be 2.93 and 2.95 gal/bushel in dry mill plants, respectively, based on extrapolation from previous data (Wang et al. 2012). Distillers' grains and solubles (DGS) are a valuable coproduct from corn dry milling ethanol plants. 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 coproduct, assuming that it displaces animal feed (corn, soybean meal, and urea). Approximately 80% of dry mill plants coproduce corn oil at an average production rate of 0.188 lb/gal of ethanol (Wang et al. 2014). Table 10 shows the assumptions for key parameters in GREET for corn-based ethanol (Wang et al. 2012; Wang et al. 2014; Liu et al. 2021).

4.3.2. Corn Ethanol Stover

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 ⅓–½ of corn stover can be sustainably removed (i.e., without causing erosion or deterioration of the soil quality; (Sheehan et al. 2008; DOE 2014; Wang et al. 2012). Stover removal results in the removal of N, P, and K nutrients, thus the nutrients lost with stover removal are typically replenished with synthetic fertilizers. The replacement rates are estimated by Han et al. (2011) based on data for nutrients contained in harvested corn stover. We account for the N_2O emissions associated with the use of supplemental N fertilizer. We also account for energy used for corn stover collection and transportation to the ethanol plant (see Table 11 for key parameters of corn stover pathways in GREET 2020).

Table 10. Assumptions for the corn ethanol production pathway used in GREET 2020

Parameter	Value
Corn farming: per bushel of corn (except as noted)	
Energy use for corn farming	6,588 Btu
N fertilizer application	364 g
P_2O_5 fertilizer application	133 g
K_2O fertilizer application	139 g
Limestone application	1,228 g
N in N_2O as % of N in of N fertilizer and biomass	1.225%
Corn ethanol production (dry mill plants)	
Share of dry mill plants with oil extraction	80%
Ethanol plant energy use (with oil extraction)	26,400 Btu/gal of ethanol
DGS yield (with oil extraction)	5.36 lb/gal of ethanol
Corn oil yield (with oil extraction)	0.19 lb/gal of ethanol
Enzyme and yeast assumptions	
Enzyme use	0.001 ton/dry ton of corn
Yeast use	0.00036 ton/dry ton of corn

Table 11. Assumptions for the corn stover ethanol production pathway

Parameter	Value	Source
Corn stover collection per dry ton of biomass		
Energy use for collection	195,500 Btu	Wang et al. (2014)
Supplemental N fertilizer	7,000 g	Wang et al. (2014)
Supplemental P fertilizer	2,000 g	Wang et al. (2014)
Supplemental K fertilizer	12,000 g	Wang et al. (2014)
Cellulosic ethanol production per dry ton of biomass (except as noted)		
Ethanol yield	79 gal	Elgowainy et al. (2020)
Electricity yield	142 kWh	Elgowainy et al. (2020)
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.

4.3.3. Soybeans to FAME

The soybean-based biofuels pathway consists of soybean farming, fertilizer production, transportation and crushing for oil extraction, soy oil transesterification to produce FAME, and biofuel transportation for use in vehicles (see Figure 5). The yield of intermediate products, such as soy oil and soybean meal, are employed to estimate the energy and emissions burden of the product (i.e., FAME).

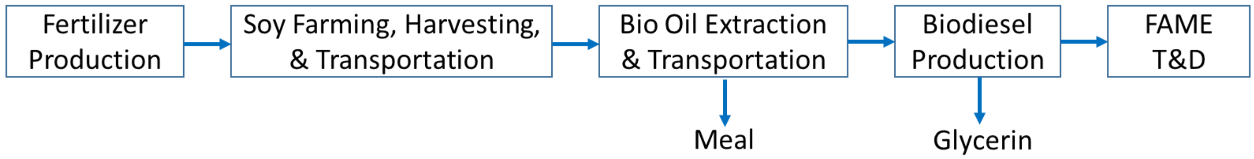

Figure 5. Soybean pathway to produce FAME

The key parameters for soybean farming, soy oil extraction, and vegetable oil transesterification processes associated with the soybean biodiesel pathway in GREET 2020 are documented in Chen et al. (2018). Table 12 and Table 13 summarize the key parameters for FAME production processes.

For the FAME pathway, oil extraction and processing are two key life cycle stages that contribute to energy use and GHG emissions. 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 coproduced. Soy meal is valuable animal feed and produces large GHG emission credits. Soybean crushing and soy oil transesterification assumptions are provided in Chen et al. (2018).

Table 12. Assumptions of energy use, fertilizer use, and N_2O emissions for soybean farming

	Soybean (per bushel)
Farming energy use: Btu	18,433
Fertilizer use	
Grams of N	48.1
Grams of P_2O_5	186.7
Grams of K_2O	299.1
Grams of $CaCO_3$	0.0
N_2O emissions from N fixation: grams N_2O	7.3
N_2O emissions: N in N_2O as % of N in N fertilizer	1.325%
N_2O emissions: N in N_2O as % of N in biomass	1.225%

Table 13. Soybean crushing and soy oil transesterification assumptions

Parameter	Value
Soybean crushing for soy oil production	1.01 lb oil/lb FAME
Energy input	3,073 Btu/lb soy oil
Oil extraction	
Oil yield	0.215 lb oil/lb dry soybeans
Soy meal yield	3.63 dry lb/lb oil
Soy oil transesterification for FAME production	
Energy input	1,516 Btu/lb FAME
Yield of FAME	1.038 lb /lb oil
Glycerin coproduct yield	0.091 lb/lb FAME

The treatment of coproducts (such as meal and glycerin) can have a significant impact on the WTW results (Wang et al. 2011). Commonly applied coproduct handling methods for fuel production processes are the energy allocation method and the displacement method (also known as the substitution or system expansion method). In the energy allocation method, energy and emissions burdens are allocated to each coproduct 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 coproducts and their applications are distinct (e.g., co-producing meal and fuel). In contrast, the displacement method 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 coproducts being displaced.

The allocation boundary for coproduct handling methods is another important issue for oil-based biofuels because coproducts are produced in two stages: oil extraction and FAME production. The oil extraction stage produces meal along with the extracted oil and the FAME production process coproduces glycerin along with FAME. A system-level approach aggregates the two stages into one, thus combining all energy/chemical inputs and coproducts into a single process. In this method, vegetable oil is considered to be an intermediate (internal product), thus the uncertainty of its properties (such as heating or market values) does not affect WTW results. Alternatively, in a process-level approach, energy/chemical inputs and coproducts for each stage are treated separately (Han et al. 2013). The impacts 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 inherently high uncertainties related to supply and demand. These effects are usually estimated using global economic models, such as the Global Trade Analysis Project (GTAP) developed at Purdue University (Taheripour and Tyner 2013). When land is converted to produce feedstock for biofuel, aboveground and belowground (or soil) carbon content often changes. The changes in aboveground biomass are of particular importance when considering the conversion of land to or from forests. Soil organic carbon (SOC) content may also decrease or increase depending on the nature of the crop, soil type, weather, and prior land use. We estimate domestic and international LUC GHG emission impacts for use in GREET by developing the Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) emissions model (Dunn et al. 2014a). In CCLUB, we combine the LUC data generated by GTAP and carbon stocks of land types from three sources. First, aboveground carbon stock data for forests comes from the Carbon Online Estimator developed by the U.S. Department of Agriculture and the National Council for Air and Stream Improvement (Van Deusen and Heath 2013; Dunn et al. 2014a). SOC changes for the relevant land transitions are estimated with a parameterized version of the process-based CENTURY model (Kwon et al. 2013). The 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 the SOC equilibrium to change. A negative change from the SOC equilibrium position results in carbon release into the atmosphere until a new equilibrium is reached. The time to reach an SOC equilibrium depends on many factors but is likely to occur within 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 for a 100-year time horizon for the LCA of any product

(British Standards Institution 2011). When long time horizons are adopted, future emissions may be discounted, although the methodology for these discounts can vary. 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 amortizing total LUC GHG emissions over the biofuel production volume during the same period (Dunn et al. 2014a). This approach aligns with the EPA LCA methodology for the renewable fuel standard (Regulation of Fuel and Fuel Additives 2010).

For this analysis, GREET 2020 and Kwon et al. (2020) (i.e., CCLUB) are used to calculate LUC GHG emissions associated with corn and corn stover ethanol production, which includes the impacts of land management change (LMC) on SOC changes when corn stover is harvested as cellulosic ethanol feedstock. Similar to LUC, SOC modeling employs CCLUB to estimate LMC-driven SOC changes associated with U.S. corn grain and cellulosic feedstock production (Qin et al 2015, 2018).

In the 2020 version of CCLUB, the LUC estimates were updated with a weighted average based on county-level corn harvested areas as the U.S. national emission factor, resulting in 7.4 and -0.6 g CO_2e/MJ for corn and corn stover ethanol, respectively. For soy biodiesel production, CCLUB estimates 9.3 g CO_2e/MJ (GREET2020; Kwon et al. 2020). However, CCLUB does not include LUC GHG modeling for HRD production, hence it is not included in this analysis.

4.3.5. Pyrolysis of Cellulosic Biomass

The renewable liquid hydrocarbon fuels produced from *ex-situ* catalytic fast pyrolysis (CFP) are included in this study as a drop-in replacement for conventional fuels used in internal combustion engines. A joint national lab team developed a design case for a conversion process that uses a blend of logging residues and clean pine as the feedstocks. The design case is a major improvement in terms of biofuel yield and energy efficiency over the fast pyrolysis case in the previous C2G study (Elgowainy et al. 2016), where significant hydrogen is needed to deoxygenate, stabilize, and upgrade the pyrolysis oil. Details of the environmental LCA and techno-economics of the CFP design case are provided in Cai et al. (2020) and Dutta et al. (2015 and 2020) and summarized in Table 14.

Table 14. Assumptions about the production of CFP-based liquid fuels from forest residue blend

	CFP of Forest Residue Blend
Farming / Collection Energy Use	139,910 (Btu/dry ton)
Plant Energy Use	45,000 (Btu/gge*)
Fuel Product Yield	61.56 (gge/dry ton)
Co-products	3.54 kWh electricity/gge 1.1 lb/gge (Methyl Ethyl Ketone +Acetone)
Land Use Change (LUC)	None

* gge=gallon of gasoline equivalent

4.4. Electro Fuel Pathways: Fischer-Tropsch Fuel Production from Hydrogen and CO_2

E-fuels are synthetic hydrocarbon fuels (e.g., Fischer-Tropsch fuels) produced by utilizing waste CO_2 streams, with electricity as the primary source of energy, for replacing or blending with their fossil counterparts. Electrolysis and synthesis are key technologies for e-fuels production, in which water is split via electrolysis into oxygen (O_2) and hydrogen (H_2), which then reacts with the CO_2 to form hydrocarbons. There is an abundant supply of high-purity CO_2 in the U.S., with around 44 million metric tons produced in ethanol plants each year. In this study, we select high-purity CO_2 as the carbon source for e-fuel production to avoid the cost and energy consumptions for CO_2 capture from flue gas.

Hydrogen is an energy carrier proposed for energy storage to enable higher penetration of renewables in the power sector, and to decarbonize the transportation and industrial sectors through clean and efficient use of its chemical energy. In particular, e-fuels provide the opportunity to decarbonize transportation applications that may be difficult to electrify through battery electric or fuel cell technologies (e.g., aviation, marine, and rail), while also overcoming the near-term need for building new H_2 distribution infrastructure.

Fischer-Tropsch (FT) fuel is compatible with conventional transportation fuels (e.g., for diesel and jet engine applications), and thus can be used for both on-road and off-road applications. FT fuel can be synthesized by using the reverse water-gas shift reaction followed by the FT synthesis process, with syngas (a mixture of CO and H_2) as an intermediate. Zang et al. simulate the FT production process from H_2 and corn ethanol byproduct CO_2 using Aspen Plus (2021a). The process is modeled for a capacity of 350 tonne/day, utilizing pure CO_2 supplied at a rate of 2,390 tonne/day by a corn ethanol plant, while also receiving hydrogen produced via water electrolysis using solar or wind energy and transported to FT plant.

The energy inputs and efficiencies of the stand-alone FT fuel production process, with and without H_2 recycling, are shown in Table 16. The energy inputs are H_2 and electricity (for process power needs), and the system energy outputs are FT liquid fuels (a mixture of naphtha, jet fuel, and diesel).

Table 15. Aspen Plus simulation results, input, and output energy in units of GJ/hr (LHV) for the FT fuel production process

	Energy type	**GJ/hr**
Input	H_2 energy	1,112
	Electricity	13
Output	Naphtha	168
	Jet fuel	302
	Diesel	177
FT fuel production efficiency[a]		57.5%

[a] The FT fuel production efficiency is defined as the ratio of total fuel energy output (i.e., the energy summation of naphtha 26%, jet fuel 47%, and diesel 27%) to the total energy input

The WTW GHG emissions of the FT fuel production process using GREET for the CO_2 and H_2 sources considered is 9 g CO_2e/MJ when using a nuclear electricity pathway, whereas it is 4 g CO_2e/MJ when using a renewable electricity pathway.

4.5. HYDROGEN PATHWAYS

Hydrogen is an energy carrier that can be produced from various feedstocks and 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 low molecular weight of hydrogen requires significant compression and/or cooling to increase its volumetric energy density for transportation, distribution, onboard storage, and refueling (Figure 6). The compression and conditioning of hydrogen requires electricity use, which may generate emissions at the power plant depending on the energy source. These emissions are accounted for in the WTT stage of the fuel cycle. The hydrogen analysis (H2A) models for H_2 production (DOE 2015), developed by the National Renewable Energy Laboratory (NREL), and the Hydrogen Delivery Scenario Analysis Model (HDSAM), developed by Argonne, are used for the pathways considered in this study for FCEVs (Elgowainy et al. 2015). The H_2 production models focus on the production processes after biomass, NG, or electricity 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 2020 model to evaluate WTW GHG emissions of various H_2 production and delivery pathways. An NREL report 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 (Connelly et al. 2020).

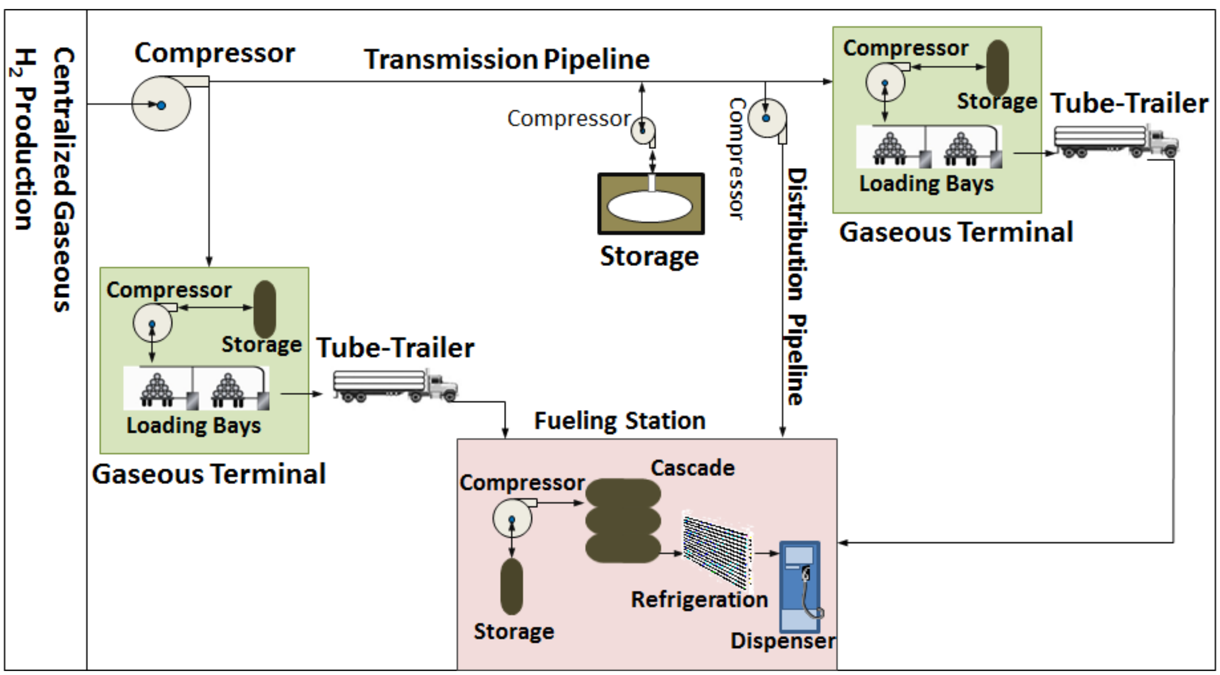

Figure 6. Hydrogen production and delivery pathways

4.5.1. SMR of NG

In SMR, 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 at 3–25 bar 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.

Hydrogen production via the NG SMR pathway in GREET 2020 is based on a recent study by Sun et al. (2019). Sun et al. (2019) investigated U.S. stand-alone SMR facilities and reported criteria air pollutant and GHG emissions per unit of hydrogen produced, using SMR facility emission data reported in the National Emissions Inventory and the Greenhouse Gas Reporting Program databases, respectively. The study summarized CO_2 emissions from combustion and chemical conversion processes. The reported median CO_2 emission normalized for SMR hydrogen production was 9 kg CO_2/kg H_2. The SMR energy efficiency was calculated based on a report from the industrial gas supplier Praxair (Bonaquist 2010) which provided CO_2 emissions for each operation step at a large central hydrogen production plant producing ~ 240 metric ton/day. Bonaquist (2010) reported that about 6.4 lb steam was exported per lb of hydrogen, and that about 290 ton/day CO_2 was emitted from NG combustion for steam export, but the thermodynamic state of exported steam was not reported. Thus, we traced the reported CO_2 emissions for steam export to NG and assumed a 90% boiler efficiency to estimate the amount of steam coproduct at 145,000 btu per mmBtu of produced hydrogen.

The SMR efficiency calculated by Bonaquist (2010) was 72% (LHV based), which is consistent with the efficiency calculated by the H2A H_2 production model. The H_2 production efficiency and coproducts in GREET 2020 for the NG SMR pathway is provided in Table 16. The SMR with CCS case is based on H2A H_2 production model version 3.0 (DOE 2015). The energy for CCS from the H2A model is 357 kWh/ton of carbon.

Table 16. Energy efficiency of hydrogen production via SMR

	Production Efficiency (LHV basis)	Steam Byproduct	Fueling Electric Energy Use*
NG SMR	72%	145,000 (Btu/mmBtuH2)	3 (kWh/kg_{H2}) for compression to 950 (bar) and precooling to -40^oC

* GHG emissions associated with electricity use for fueling of FCEV is based on US grid average generation mix

4.5.2. Water Electrolysis

Hydrogen can be produced via the electrolysis of water. However, the electrolysis process requires a significant amount of electricity, which exceeds the energy in the produced hydrogen. The production efficiency of H_2 via low-temperature electrolysis using polymeric exchange membrane is 66.8% based on the H2A model (Elgowainy et al. 2013). The GHG emissions intensity of hydrogen production via water electrolysis depends mainly on the carbon intensity of the electricity. The desire to minimize GHG emissions associated with H_2 production via electrolysis requires electricity to be generated from clean 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. This study also evaluates hydrogen production via high-temperature electrolysis using nuclear power and steam in solid oxide electrolysis cell, using a conversion factor of 14.2 MWh of H_2 per gram of U-235 in GREET 2020.

4.5.3. Hydrogen Delivery (Transmission, Distribution, and Refueling)

Today and in the near future, assuming on low FCEV adoption, H_2 transmission and distribution to refueling stations will likely be via trucking, while long-term, high-volume transportation economics should favor H_2 pipeline transmission and distribution. GREET assumes that production plants generate H_2 at a pressure of 300 psi (20 bar).

For pipeline delivery, it is assumed that 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 100 miles. 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 the 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 (1):

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

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 those for vehicle refueling, compression is assumed to occur 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 and precooling electric energy consumption is estimated at 3 kWh/kg.

While H_2 is not a greenhouse gas, it can impact global warming by competing with CH_4 for the OH^- radical in the atmosphere. Literature reports show preliminary estimates for indirect global warming potential (GWP) over 100 years of H_2 in the range of 3-20. Future versions of GREET will incorporate GWP for H_2 to assess the potential impact of H_2 leakage throughout the supply chain. However, that is not included in this present analysis.

4.6. Gas To Liquid Pathways

The FT synthesis process produces diesel-like hydrocarbon fuel (i.e., FTD) from syngas. Since 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. A LCA of FTD shows that CCS is needed to achieve significant WTW GHG emissions reductions 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 calculate 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). In 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 (1) 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.

4.7. Electricity Pathways

Total electricity generation in the U.S. has historically increased but remained relatively stable over the past two decades. However, the recent trend of fuels consumed for electricity generation show increased shares of NG and renewable power generation, and a reduced share of coal power generation. Furthermore, recently installed power generation technologies (e.g., NG ACC) have improved energy efficiencies and reduced environmental impacts. Ou and Cai analyze generation unit-level data for thermal performance and emissions of electric generating units (EGUs) (2020). 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 (U.S. Geological Survey 2006), as documented by Cai et al. (2012).

The electricity generation mix used in this study represents 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 17 for the years 2020 and 2035 for use in this analysis (GREET 2020, which uses AEO 2020). Generation technology shares are determined by the ratio of the amount of electricity generated by each technology to the total electricity generation. Table 18 The LHV-based energy efficiencies and generation technology shares (for each fuel type) of thermal EGUs. The electricity transmission and distribution losses are assumed to be 4.9% (Ou and Cai, 2020).

Table 17. U.S. average generation mix in 2020 and 2035 (%)

Fuel	2020	2035
Residual oil	0.4	0.2
NG	36.8	36.0
Coal	22.8	17.1
Nuclear power	20.3	15.0
Biomass	0.3	0.3
Other renewables	19.4	31.4

Table 18. Energy efficiencies and generation technology shares of thermal EGUs (%)

Fuel	Combustion Technology	Generation Efficiency	Share of Generation Technology by Fuel
Coal	Steam cycle	34.5	100
	Integrated gasification combined cycle	39.0	0
NG	Steam cycle	33.8	7.1
	Combustion turbine	32.9	8.8
	ACC	51.6	83.1
	Internal combustion engine	41.0	1.0
Oil	Steam cycle	32.6	76.6
	Combustion turbine	26.9	13.5
	Internal combustion engine	34.9	9.9
Biomass	Steam cycle	21.7	100

4.8. Changes to Default Estimates from GREET2020

The following changes were made to the public release of GREET 2020 for this study.

E-fuels GHG emissions factors: The life cycle GHG emissions for e-fuels were derived from Zang et al. (2021a). That analysis determined that GHG emissions for e-fuels from the nuclear pathway were 9 g CO_2e/MJ, whereas it was 4 g CO_2e/MJ for the renewable pathway. Those values are used in this study.

GHG emissions factors for pyrolysis, E85 from corn, and E85 from corn stover: The life cycle GHG emissions for gasoline from forest residue pyrolysis, E85 from corn, and E85 from stover were discussed in Section 4.3 and derive from Elgowainy et al. (2020). The resultant GHG emissions associated with pyrolysis gasoline, E85 from corn, and E85 from corn stover are 50.1 g CO_2e/MJ, 12.4 g CO_2e/MJ, and 16.2 g CO_2e/MJ, respectively.

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.

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5. FUEL PATHWAYS: COST ASSUMPTIONS AND DATA SOURCES

The cost analysis of the various fuel pathways in this study builds from approaches established in the 2016 C2G report (Elgowainy et al. 2016). Below we provide an updated description of cost assumptions and data sources to reflect changes made in the current analysis. As in the 2016 study, this cost analysis is developed from several sources of publicly available data and models: (1) the EIA 2021 AEO (EIA 2021a), (2) external cost assessments, and (3) publicly available alternative fuel costing models 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 uses a variety of models and external sources to determine the cost of dispensed fuel to final consumers (not at the production-plant gate), less federal and state fuel taxes, reported on a $/gge (gasoline gallon equivalent) basis in 2020$.[6] Fuel costs are developed for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases (MY2020 and MY2030–2035, respectively). For hydrogen, which is still at low volumes today as a retail fuel, a CURRENT TECHNOLOGY, LOW VOLUME of hydrogen cost is also estimated.

In general, fuel cost data are taken from the 2021 AEO (EIA 2021a), if available, and from various TEA models developed by DOE to assess the cost of alternative and renewable fuels for fuel not included in AEO. Costs in AEO 2021 account for feedstock costs, capital costs, operating cost, and return on capital commensurate with risk factors (EIA 2021c). Where possible, TEA models are revised by the C2G team to use a consistent set of assumptions and financial parameters (see Table 19).

The remainder of this section provides details on how cost modeling is conducted for the fuel pathways investigated in this study, as well as the resulting fuel cost estimates for these pathways. An overview of the key assumptions, data sources, and cost results is provided in Table 20 and Figure 7. The resulting fuel costs are used in Section 9 as inputs to the LCD assessments.

Table 19. Common assumptions used in fuel cost modeling

Metric	Assumption
IRR	10%
Dollar value year	2020
Finance rate	All equity
[Facility] depreciation rate	20-year Modified Accelerated Cost Recovery System
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 2021 (average U.S. grid mix and new generation sources)
[Internal] NG	AEO 2021
Biomass feedstock(s)	$100+ per short ton (CURRENT TECH) $80 per short ton (FUTURE TECH)
Assumed scale/volume	At/above optimal scale except where noted

6 Gasoline gallon equivalent (gge) is a measure based on energy content. In this study, gge is defined as 112,194 Btu of energy on an LHV basis, based on a mix of 90% gasoline blendstock and 10% (denatured) ethanol on a volume basis.

Table 20. Fuel cost assumptions (2020$/gge)[a]

Fuel / Feedstock		CURRENT TECH	FUTURE TECH (low/base/high)	Notes
Crude oil	$/barrel to refinery	40	42/81/156	EIA AEO 2021 average price to refinery (Low Oil case, Reference case, High Oil case)
Gasoline	Petroleum	1.69	1.56/2.37/3.7	AEO 2021 (Low Oil case, Reference case, High Oil case), taxes removed
	Pyrolysis		3.60	Dutta, A. et al. (2021); costs reported in 2020$ (converted from 2016$ basis in the reference), distribution and dispensing costs added
	E-fuels (nuclear)		5.19	Elgowainy et al. (2020), distribution and delivery added
	E-fuels (renewable)		5.19	Elgowainy et al. (2020), distribution and delivery added
Diesel	Petroleum	1.67	1.65/2.47/3.85	AEO 2021 (Low Oil case, Reference case, High Oil case), taxes removed
	Pyrolysis		3.60	Dutta, A. et al. (2021); costs reported in 2020$ (converted from 2016$ basis in the reference), distribution and dispensing costs added
	E-fuels (nuclear)		5.19	Elgowainy et al. (2020), distribution and delivery added
	E-fuels (renewable)		5.19	Elgowainy et al. (2020) distribution and delivery added
CNG	CNG	1.57	1.8/1.44/1.49	Alternative Fuels Data Center for CURRENT TECHNOLOGY with taxes removed, AEO 2021 for FUTURE TECHNOLOGY (Low Oil case, Reference case, High Oil case), compression cost included, taxes removed
	Renewable natural gas (RNG)		1.85	Gasper and Searchinger (2018), compression, and distribution and delivery added
Ethanol	E85 (corn)	2.08	2.04/3.06/4.76	AEO 2021 (Low Oil case, Reference case, High Oil case), taxes removed
	E85 (corn stover)		3.83	Tao, L., et al. (2014); updated costs to 2016$ and updated feedstocks costs, onstream factor, 80 gal/dry ton biomass ethanol yield and tax rate; distribution and dispensing costs added
Electricity	Average grid mix	4.01	4.10	AEO 2021 (average U.S. grid mix)
	NG ACC w/CCS	-	4.04	EIA 2015, EIA 2020
	Wind (with storage)	-	4.76	AEO 2021 (average grid mix, 4.11 $/gge) + 2 c/kWh for integration of intermittent renewables
	Solar PV (with storage)	-	4.76	AEO 2021 (average grid mix, 4.11 $/gge) + 2 c/kWh for integration of intermittent renewables
Hydrogen	NG SMR	7.30 (HIGH-VOL) /11.80 (LOW-VOL)	-	H2A + HDSAM
	NG SMR w/CCS		4.00	Based on DOE HFTO Target of $1.00/kg H_2
	Low-Temp Electrolysis Wind/Solar PV		4.00	Based on DOE HFTO Target of $1.00/kg H_2
	High-Temp Electrolysis Nuclear		4.00	Based on DOE HFTO Target of $1.00/kg

[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 2021-sourced data, the base case corresponds to the AEO 2021 reference case value for 2020.

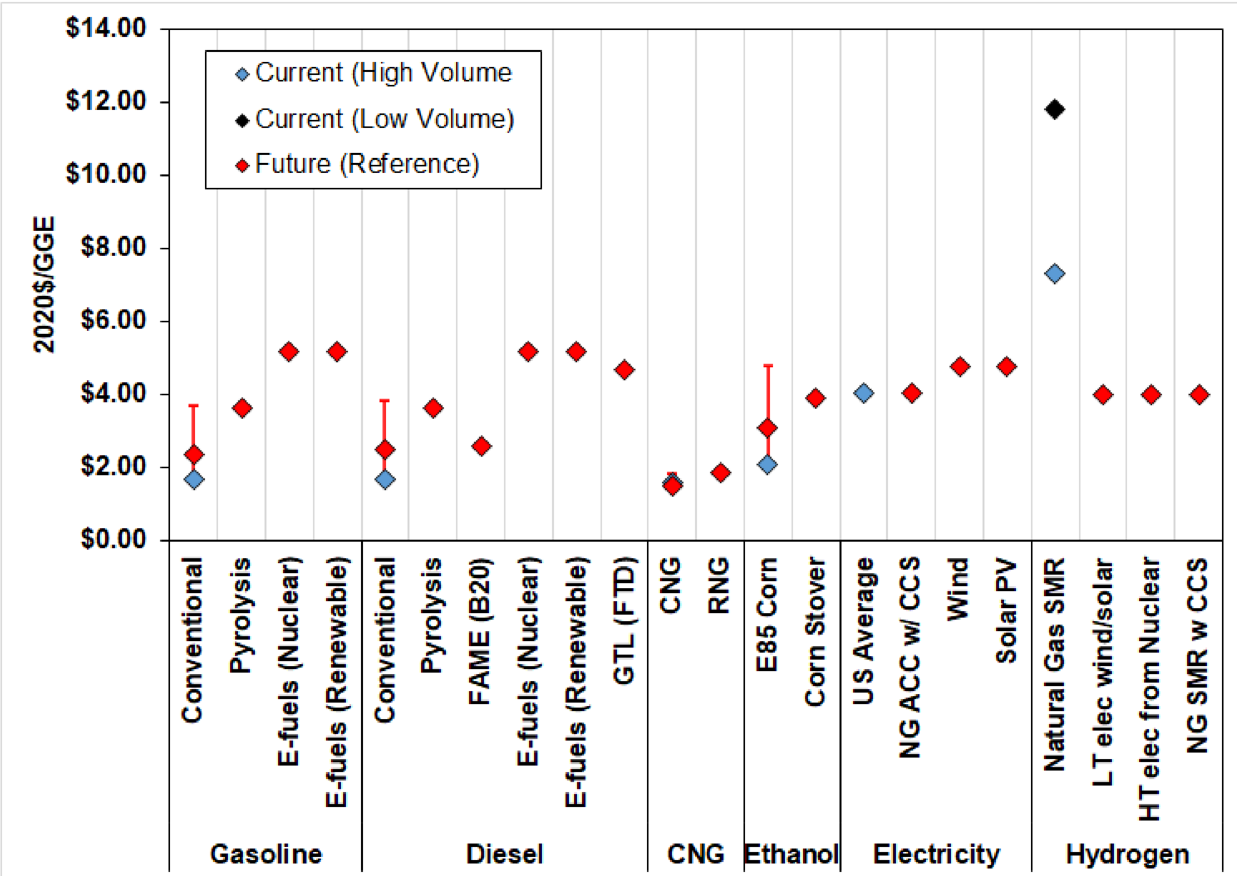

Figure 7. Summary of fuel cost results

5.2. Transportation Fuel Cost Estimates from AEO 2021

Fuel costs for conventional gasoline, conventional diesel, ethanol (E85) from corn (starch), and CNG are based on AEO 2021. Specifically, the AEO 2021 reference case "Energy Prices by Sector and Source" data are used to provide base case fuel costs in the C2G study for the CURRENT TECHNOLOGY (2020) and FUTURE TECHNOLOGY (2030-2035) cases. For the FUTURE TECHNOLOGY cases, AEO 2035 projections are used. High and low fuel costs for the FUTURE TECHNOLOGY case are based on the AEO 2021 "High Oil Price" and "Low Oil Price" cases, respectively, and are used for sensitivity analysis in Sections 9.3 and 10.4.

AEO 2021 cost data are provided in 2020$, with fuel costs provided in $/MMBtu. AEO cost estimates also include fuel taxes. To obtain fuel prices in $/gge excluding taxes (basis for this study), AEO fuel prices were revised as follows:

- Prices are converted from $/MMBtu to $/gge based on a LHV Btu/gge conversion factor.
- Federal Tax, State Tax, and Energy Tax/Allowance Fee cost components from AEO 2021 are removed. (This differs slightly from the approach of the 2016 report, in which only Federal Tax and State Tax were removed.)

As AEO 2021 costs represent the cost for fuel delivered to consumers, no additional costs for distribution and dispensing are included.

5.3. Pyrolysis Fuels

This section includes projections for both gasoline and diesel fuels from pyrolysis pathways for the Future Technology, High Volume case. The benchmark pathway used as a reference point for the cost projection assumes a catalytic pyrolysis derived-intermediate is finished at a petroleum refinery via coprocessing with fossil-derived hydrocarbons in a hydrotreater. Pyrolysis fuel costs are based on Dutta et al. (2021), which includes projections based on the scale-up of 2020-21 bench-scale experimental performance in a modeled conceptual process with 2000 dry tons/day of woody biomass throughput. The projected base case cost of production (without dispensing and distribution added) was $3.24/GGE in 2020$ (reported as $2.83/GGE in 2016$ in Dutta et al. 2021). This fuel pricing for the Future Technology, High Volume case of $3.24/GGE is based on model assumptions for a scaled-up mature or n^{th} plant design, with financial assumptions consistent with analyses performed under DOE Bioenergy Technologies Office (BETO) and detailed in Dutta et al. Note that the assumed GGE LHV basis for Dutta et al. was 116,090 Btu/gal, while the basis in this study is for blended gasoline used in the market (112194 Btu/gal). Thus, the cost is adjusted to $3.13/GGE in 2020$.

The $3.13/GGE 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). We use the average of these cost estimates for the distribution and dispensing cost. For biomass pyrolysis fuels, the distribution cost is $0.47/GGE in 2020$. Together with the plant-gate production cost, this yields a dispensed cost of pyrolysis-derived gasoline or diesel of $3.60/GGE in 2020$.

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 2021 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 on an energy (lower heating value) basis.

5.4. Ethanol Fuels from Corn Stover

An ethanol (E85) from corn stover pathway is included as part of the Future Technology case analysis[7]. 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, we rely 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, data from a variety of public sources were used 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.

For the corn stover E85 cost estimation, feedstock costs were assumed to be $84.45/dry short ton (in 2016$), which is consistent with the assumptions used in BETO (DOE 2019). Facility capacity utilization (on-stream factor) was assumed to be 90%, consistent with BETO-supported hydrocarbon pathways

7 The Current and Future Technology cases consider E85 from corn ethanol using costs from AEO 2021, as noted in Section 5.2.

design cases (Davis 2013), as well as USDA reporting on the capacity utilization of starch-based ethanol plants (USDA 2015).

Using these assumptions, coupled with those detailed in Section 4.3.2, results in a neat ethanol cost of $2.52 per gallon of ethanol (Tao 2014). This is then converted to the GGE basis for this study, resulting in a cost of $3.70/GGE for neat ethanol. But does not include costs associated with distribution and delivery, thus those costs are adapted from Cazzola et al. (2013) as noted in Section 5.3 ($0.47/GGE) and added to the neat ethanol cost to yield a total of $4.17/GGE. This neat ethanol is blended at 83% by volume with 17% gasoline to result in E85 at a cost of $3.87/GGE 2020$.

5.5. ELECTRICITY

Electricity used as an upstream energy source is assumed to be U.S. grid mix electricity based on AEO 2021 data. Similarly, electricity for electric vehicle charging in the CURRENT TECHNOLOGY case is based on AEO 2020 residential cost data for the U.S. AEO cost data in $/MMBtu are converted to $/gge using the conversion factor of 112,194 Btu/gge (32.88 kWh per gge). The resulting 2020 cost of residential electricity for electric vehicle charging is $4.01/gge.

For the FUTURE TECHNOLOGY case, several advanced and renewable electricity generation pathways are investigated for charging, electric vehicles.[8] Advanced electricity generation pathways include:

- NG ACC with CCS
- Solar PV electricity
- Wind electricity

The cost for NG ACC with CCS is derived from a 2015 EIA study on new generation (EIA 2015) and then scaled to align with a similar 2021 report by EIA (EIA 2021a). The reason for the scaling was because the 2021 report only included NG ACC, but not NG ACC with CCS. Thus, the relative relationship between NG ACC and NG ACC with CCS cost components (levelized capital cost, fixed operation and maintenance, variable operations and maintenance including fuel, and transmission investment) from the 2015 study are applied to the NG ACC costs in 2021 to estimate the cost of an NG ACC with CCS. This generation cost is then combined with transmission and distribution costs, as specified in AEO (EIA 2021a). For solar and wind, while levelized costs at the source (solar PV array or wind turbine) are often lower than typical wholesale rates, the intermittency of these sources imposes a cost burden onto the distribution system as a whole. To account for this burden, which will include load management and energy storage, an additional $0.02/kWh was added to the AEO2021 2035 projected residential electricity cost. The additional cost was based on the research team's internal analysis of EIA AEO 2020 generation mix cases and levelized cost of electricity (EIA 2020a).

Infrastructure costs associated with residential charging (e.g., charging infrastructure, or electric vehicle supply equipment (EVSE), equipment and installation costs) are not included in these electricity costs, but have been added as an up-front cost. However, that cost is not combined with the vehicle cost when presenting the cost of the vehicle. The assumed residential charging cost was $1,836 per BEV, and half of that—$918—for PHEV based on Borlaug et al. (2020). We do not include non-residential EVSE costs in this analysis.

[8] 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 analysis.

Table 21. AEO 2021 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)	Green Premium[b] ($/kWh)	Final Price to Consumer ($/kWh)	Electric Vehicle Fuel Cost ($/gge)
CURRENT TECHNOLOGY case (2020)					
Average AEO 2020 grid mix	0.068	0.054		0.122	4.01
FUTURE TECHNOLOGY case (2035)					
Average AEO 2035 grid mix	0.064	0.061		0.125	4.10
NG ACC with CCS	0.046	0.061	0.016	0.123	4.04
Wind (US mix + green premium)	0.064	0.061	0.020	0.145	4.76
Solar PV (US mix + green premium)	0.064	0.061	0.020	0.145	4.76

[a] Cost data is expressed in 2020$.

[b] Green premium is an add-on cost for CCS (NG ACC) or integration of intermittent renewables (wind/solar)

5.6. E-FUELS

We conduct a detailed TEA to estimate the minimum selling fuel price (MSFP) of FT fuels produced from carbon dioxide and hydrogen (Zang et al., 2021b). The MSFP of FT fuels strongly depends on the cost of delivered CO_2 and H_2, in addition to the capital cost of the FT plant and other economic and financial assumptions. The H_2 price has the largest impact on the MSFP of FT fuel. The H_2 cost from water electrolysis depends on three key factors: (1) the electrolyzer price, (2) the electrolyzer capacity factor, and (3) the electricity price. The CO_2 price depends mainly on its purity level, scale of production, and distance from the FT plant. FT fuel production, with a CO_2 price of $17.3/metric ton (consistent with a high purity source from corn-ethanol plant), requires a H_2 cost of $0.8/kg to be cost-competitive with the pre-tax petroleum diesel price of $3.1/gge. The breakeven H_2 cost is a function of the FT plant carbon conversion ratio and energy efficiency (i.e., FT product yield) and the untaxed price of the incumbent baseline fuel. FT plants with higher yields and energy conversion efficiencies, and untaxed diesel prices higher than $3.1/gge, allow the breakeven H_2 cost to be higher than $0.8/kg. When the H_2 cost is $2/kg from central water electrolysis (consistent with the H_2 cost target), the MSFP of the FT fuel mixture is $5.4/gge.

5.7. HYDROGEN FUEL

This report analyzes life cycle GHG emissions and LCD for various hydrogen pathways assuming current (2020) technology and fuel pathways, and pathways assumed to be viable by 2035.

To estimate costs in the CURRENT TECHNOLOGY scenario, this analysis uses two publicly available TEA models developed for DOE to estimate the levelized cost of hydrogen production, delivery, and dispensing: H2A Production Models (DOE H2A Production Analysis, 2015) and the HDSAM (Elgowainy et al. 2015). H2A is a set of models that use discounted cash flow analysis to estimate the levelized cost of hydrogen production. Levelized cost estimates are based on financial inputs, technology parameters, and operational parameters, such as the price of energy feedstock, the capital cost of technology, process efficiency, capacity utilization, and operations and maintenance costs. Similarly, HDSAM is a discounted cash flow model that evaluates the levelized cost of hydrogen delivery and dispensing in a wide range of scenarios, based on parameters such as delivery mode, station capacity, manufacturing volume, equipment efficiency, system utilization rate, and operating and maintenance costs.

The C2G analysis evaluates two CURRENT TECHNOLOGY and three FUTURE TECHNOLOGY cases for hydrogen technology pathways, described in the bulleted list below. In the CURRENT TECHNOLOGY cases, hydrogen delivery is assumed to occur via gaseous tube trailer, and hydrogen dispensing is assumed to occur using 300 kg/day stations. In the FUTURE TECHNOLOGY cases, the cost of hydrogen fuel (production, delivery, and dispensing) is assumed to be $4/kg, consistent with the DOE target. Emissions analysis of the FUTURE TECHNOLOGY cases is conducted assuming that hydrogen is supplied to stations via pipelines, and that stations dispense hydrogen at 700 bar. In both CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, the emissions profile of electricity supplied to hydrogen fueling stations is assumed to represent 2020 and 2035 grid mixes in the EIA's 2021 AEO (2021a).

- CURRENT TECHNOLOGY cases (2020):
  - Centralized hydrogen production via SMR, assuming current manufacturing volumes (i.e., mature market for SMR, low-volume manufacturing for delivery and dispensing)
  - Centralized hydrogen production via SMR, assuming high-volume manufacturing for all production, delivery, and dispensing technologies
- FUTURE TECHNOLOGY cases (2035):
  - Centralized hydrogen production via SMR with CCS, assuming high-volume manufacturing for all production, delivery, and dispensing technologies
  - Centralized low-temperature electrolysis using wind/solar electricity, assuming high-volume manufacturing for all production, delivery, and dispensing technologies
  - Centralized high-temperature electrolysis using nuclear energy, assuming high-volume manufacturing for all production, delivery, and dispensing technologies

The costs of hydrogen production, delivery, and dispensing assumed in the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases are summarized in Table 22 below.

Table 22. Hydrogen pathway costs for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases (2020$)

Hydrogen Pathway	Production Cost ($/gge)	Delivery and Dispensing Cost ($/gge)	Total Dispensed H_2 Cost ($/gge)
CURRENT TECHNOLOGY case (2020)			
SMR (NG SMR)	1.15	6.15	7.30
SMR LOW-VOLUME case	1.15	10.65	11.80
FUTURE TECHNOLOGY case (2035)			
Low-temp. electrolysis (wind/solar)	-	-	4.00
High-temp. electrolysis (nuclear)	-	-	4.00
NG SMR with CCS	-	-	4.00

5.8. References for Section 5

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6. VEHICLE ENERGY CONSUMPTION AND COST ASSUMPTIONS

6.1. AUTONOMIE SUMMARY

Vehicle fuel consumption and vehicle technology cost are critical inputs to estimate C2G energy use, GHG emissions, and LCD for each vehicle-fuel combination. To calculate vehicle fuel consumption and technology costs, an automotive control-system design and simulation tool is needed. This study uses Autonomie (Argonne National Laboratory, n.d.), a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. Autonomie, sponsored by the DOE VTO and developed by Argonne in collaboration with General Motors, is designed for the 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). It is designed to serve as a single tool that meets the requirements of automotive engineers throughout the development process—from modeling to control. Several Autonomie powertrain models across varying vehicle classes have been validated using Argonne's Advanced Mobility and Technology Laboratory 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, FCEV, HEV, PHEV, and BEV), a vehicle model is built based on data for each component in the main Autonomie database. Vehicle components are sized by internal algorithms to meet the same vehicle technical specification, as given in Section 6.2. After the vehicle component sizes are determined, the vehicle cost is estimated from the cost of the components. Finally, fuel consumption is simulated on the UDDS and HWFET cycles. The assumptions and results used in this report are documented in detail in Islam et al. (2021). A comparison of vehicle cost and fuel economy of the modeled and commercially available vehicles is presented in Appendix A: .

Autonomie is designed to assess vehicle technologies for five laboratory timeframes: 2015 (reference), 2020, 2025, 2030, and 2045. Laboratory year is assumed to precede market introduction by 5 years. Hence, 2015 laboratory technology and cost points are expected to appear in the market in 2020. The reference laboratory 2015 and 2025 vehicles in Autonomie are selected as CURRENT TECHNOLOGY (MY2020) and FUTURE TECHNOLOGY (MY2030–2035) vehicles, respectively. For laboratory years 2020 and beyond, uncertainties in both component performance and cost are taken into account by considering two progress levels for technology performance and cost: low (business-as-usual) and high (DOE VTO-HFTO goals). Background information on various vehicle attributes and assumptions are specified in Islam et al. (2021).

For each vehicle considered in Islam et al. (2021), the performance and cost follow an uncertainty distribution. Assumptions of technological progress affect component costs within the model (but assumptions of progress in component costs do not affect technological 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 consists of the appropriate technology progress and cost uncertainty combination. For this analysis, we use the low and high powertrain technological progress cases for MY2020 and beyond. The high powertrain technological progress case corresponds to high technological progress values for all technologies, except lightweighting. The low technological progress values for lightweighting are carried into the high technology powertrain technological progress cases. Detailed combinations of technological progress and cost cases are outlined in Islam et al. (2021).

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

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

Fuel economy results from Autonomie for gasoline, diesel, and CNG vehicles are used in this study. For HEV, a power-split configuration is used, while a series configuration is used for FCEV and PHEV50.

The PHEV50, BEV200, BEV300, and BEV400 vehicles in this study are taken from, and are identical to, the vehicles labeled PHEV50, BEV200, BEV300, and BEV400 in the Autonomie model (Islam et al. 2021). 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 technical specifications:

- Initial vehicle movement to 60 mph in 8 s ±0.1 s,
- Maximum grade of 6% at 65 mph at GVW, and
- Maximum vehicle speed >100 mph

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

- For HEVs, the electric-machine and battery powers are determined to capture the regenerative braking energy during a UDDS cycle. The engine and generator are then sized to meet the gradeability and performance requirements.
- For PHEV50s, the main electric-machine and battery powers are 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 is defined to follow the combined UDDS & HWFET cycle electric range of 50 miles, based on EPA adjustment factors.[9]
- For H_2 FCEV300 and 400, the hydrogen storage system is sized to yield a driving range of 300 and 400 miles, respectively, to follow the combined UDDS & HWFET cycles, based on EPA adjustment factors.

The detailed process of vehicle component sizing and EPA procedures for different powertrains are specified in detail in Islam et al. (2021).

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

6.3. FUEL ECONOMY AND ELECTRICITY CONSUMPTION

The primary analysis of this study assumes the high powertrain technology progression pathway for the FUTURE TECHNOLOGY midsize sedan and small SUV. The low powertrain technology progression parameters and results are available in Appendix D. Table 23 and Table 24 list the Autonomie projections of fuel economy and electricity consumption over the UDDS and HWFET driving cycles (and the corresponding on-road adjusted results). Note that the electricity consumption of plug-in electric 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 charging electricity consumption. Laboratory fuel economy testing is conducted under much milder conditions than "real-world" driving, with a 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 the EPA to estimate on-road fuel economy based on a five-cycle testing method from laboratory test results (EPA 2015), as shown below.

$$\text{On-road city fuel economy} = 1/(0.004091+1.1601/\text{ UDDS fuel economy})$$

$$\text{On-road highway fuel economy} = 1/(0.003191+1.2945/\text{ HWFET fuel economy})$$

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, the adjustment factor is capped at 0.7, following the method described by Elgowainy et al. (2010) and Stephens et al. (2013), and used by the EPA (EPA 2015).

PHEVs have two operating modes: CD and 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 EREV (PHEV50), the CD mode is all-electric. When the state-of-charge reaches a predetermined level, the vehicle switches to the CS mode, where it operates like a regular HEV.

Because there are two sources of energy and two driving modes, on-road adjustments for PHEVs are more uncertain than those for conventional vehicles. We follow the same procedure of on-road adjustment for PHEVs as Elgowainy et al. (2010) and Stephens et al. (2013) and EPA 2015. For the PHEV50, 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 PHEV50, we adjust fuel and electricity consumption by a factor of 0.7 since the on-road load is mostly met by battery power, with minor assistance from the engine. A detailed discussion of the on-road adjustment is provided in Elgowainy et al. (2010) and Stephens et al. (2013).

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, 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 values are calculated as a weighted average of UDDS (43%) and HWFET (57%) results. Note that the EPA applies the 43/57 split with respect to mpg-based fuel economy values, while the 55/45 split is applied for the (unadjusted) test cycle fuel economy values (EPA 2006). The EPA (2015) assumed the 55% city/45% highway weighting gradually changed to a 43% city/57% highway weighting in a linear fashion over the period of 1986 to 2005.

Table 23. 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 (units are in the first column)

Vehicle and Test			Test Cycle		On-road Adjusted	
			CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
Midsize Sedan	Gasoline SI Turbo ICEV (mpgge)	UDDS	37.1	51.1	28.3	37.3
		HWFET	49.6	72.1	34.1	47.3
	Diesel CI ICEV (mpgge)	UDDS	42.3	54.6	31.7	39.5
		HWFET	54.6	67.2	37.2	44.6
	CNG SI ICEV (mpgge)	UDDS	33.4	45.1	25.8	33.6
		HWFET	43.9	62.1	30.6	41.6
	Gasoline SI HEV (mpgge)	UDDS	72.3	92.1	49.7	59.9
		HWFET	67.4	87.0	44.7	55.3
	H_2 FCEV300 (mpgge)	UDDS	86.5	104.1	60.6	72.9
		HWFET	106.8	129.5	74.8	90.7
	H_2 FCEV400 (mpgge)	UDDS	84.8	102.2	59.4	71.5
		HWFET	105.8	128.5	74.0	89.9
	BEV200 (Wh/mi)	UDDS	139	120	199	172
		HWFET	171	148	245	212
	BEV300 (Wh/mi)	UDDS	145	122	207	175
		HWFET	181	154	258	219
	BEV400 (Wh/mi)	UDDS	169	139	241	199
		HWFET	193	161	276	231
Small SUV	Gasoline SI Turbo ICEV (mpgge)	UDDS	33.7	46.3	26.0	34.3
		HWFET	42.8	62.1	29.9	41.6
	Diesel CI ICEV (mpgge)	UDDS	38.7	50.1	29.3	36.7
		HWFET	47.7	63.6	33.0	42.5
	CNG SI ICEV (mpgge)	UDDS	30.4	40.8	23.7	30.7
		HWFET	38.6	53.6	27.2	36.6
	Gasoline SI HEV (mpgge)	UDDS	61.5	79.0	43.6	53.2
		HWFET	56.6	72.8	38.4	47.7
	H_2 FCEV300 (mpgge)	UDDS	72.8	88.2	50.9	61.7
		HWFET	85.9	103.9	60.1	72.7
	H_2 FCEV400 (mpgge)	UDDS	71.3	86.4	49.9	60.5
		HWFET	85.1	103.1	59.6	72.2
	BEV200 (Wh/mi)	UDDS	166	143	237	205
		HWFET	214	186	306	266
	BEV300 (Wh/mi)	UDDS	173	147	247	209
		HWFET	225	193	321	275
	BEV400 (Wh/mi)	UDDS	202	166	288	237
		HWFET	240	200	342	286

Table 24. Autonomie-modeled test cycle and on-road adjusted fuel economy and electricity consumption for the gasoline PHEV50

Vehicle and Test		Mode and Units	Test Cycle		On-road Adjusted	
			CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
Midsize PHEV50 (EREV)	UDDS	CD electric (Wh/mi)	177	156	253	223
		CS engine (mpgge)	70	95	49	66
	HWFET	CD electric (Wh/mi)	205	180	293	257
		CS engine (mpgge)	64	83	45	58
Small SUV PHEV50 (EREV)	UDDS	CD electric (Wh/mi)	206	182	295	259
		CS engine (mpgge)	59	80	42	56
	HWFET	CD electric (Wh/mi)	252	221	360	315
		CS engine (mpgge)	52	68	36	48

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 by the EPA (2015).

Table 25 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 PHEV50s 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 liquefied petroleum gas (LPG) ICEVs are assumed to be the same as those for gasoline ICEVs. Figure 8 presents the fuel economy ratios relative to the CURRENT TECHNOLOGY gasoline ICEV case for each vehicle class.

Note that the CURRENT TECHNOLOGY ICEV fuel economy case is based on a conventional turbocharged engine efficiency map. Our baseline vehicle is a conventional vehicle with a turbocharged inline four-cylinder engine with variable valve timing and variable valve lifting, a 6-speed automatic transmission, and vehicle characteristics averaged over the entire fleet (aerodynamic coefficients, rolling resistance, glider mass, etc.) for both the midsize sedan and small SUV vehicle classes. Additionally, Appendix A addresses the comparison of fuel economy and cost of the modeled vehicles from this report with MY2020 midsize cars and small SUVs sold in the retail market.

The BEV/ICEV fuel economy ratios in the present C2G study are significantly more favorable towards BEVs than in our previous study. For example, in the present study the CURRENT TECHNOLOGY BEV200 is approximately 4 times more energy efficient than the gasoline ICE (405% in Table 25) while in our previous study the BEV210 was approximately 3.2 times (324% in Table 36 of Elgowainy et al., 2016) more efficient than the gasoline ICEV. There are a number of assumptions that were different in the present Autonomie runs compared to those in 2016 which led to this improvement in the relative performance of BEVs. These changes included: (i) using a faster 0-60 mph performance time (8 instead of 9 seconds) which does not affect the energy consumption of BEVs because they already exceed this, but does affect the conventional vehicles, (ii) updated component weights (electric machine, engine, batteries, etc.) and glider weight which generally favored BEVs, and (iii) updated component performance (electric machine, engine, transmission) with the increased efficiency of the electric machine being significant.

Table 25. 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
Midsize Sedans	Gasoline SI Turbo ICEV (mpgge)	31	42	100	100
	Diesel CI ICEV (mpgge)	34	41	110	100
	CNG SI ICEV (mpgge)	28	37	90	89
	E85 SI ICEV (mpgge) [b]	31	42	100	100
	Gasoline SI HEV (mpgge)	46	56	149	135
	H_2 FCEV300 (mpgge)	67	80	217	193
	H_2 FCEV400 (mpgge)	66	79	213	191
	BEV200 (mpgge)	124	149	405	358
	BEV300 (mpgge)	118	144	385	348
	BEV400 (mpgge)	107	133	349	321
	PHEV50 (EREV)				
	CD electricity consumption (Wh/mi)	276	242		
	CD fuel consumption (Btu/mi)	2	2		
	CD distance (mi)	50	50		
	CS fuel economy (mpgge)	45.6	60.3	149	145
	CD fuel economy (mpgge)	119.1	135.5	388	326
Small SUVs	Gasoline SI Turbo ICEV (mpgge)	27	37	100	100
	Diesel CI ICEV (mpgge)	31	39	111	104
	CNG SI ICEV (mpgge)	25	33	91	89
	E85 SI ICEV (mpgge) [b]	27	37	100	100
	Gasoline SI HEV (mpgge)	40	49	144	131
	H_2 FCEV300 (mpgge)	55	66	199	177
	H_2 FCEV400 (mpgge)	54	65	196	175
	BEV200 (mpgge)	101	121	368	323
	BEV300 (mpgge)	97	117	351	314
	BEV400 (mpgge)	88	109	319	293
	PHEV50 (EREV)				
	CD electricity consumption (Wh/mi)	332	291		
	CD fuel consumption (Btu/mi)	2	2		
	CD distance (mi)	50	50		
	CS fuel economy (mpgge)	37.9	50.0	138	134
	CD fuel economy (mpgge)	98.8	112.7	360	302

[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 technological progress.

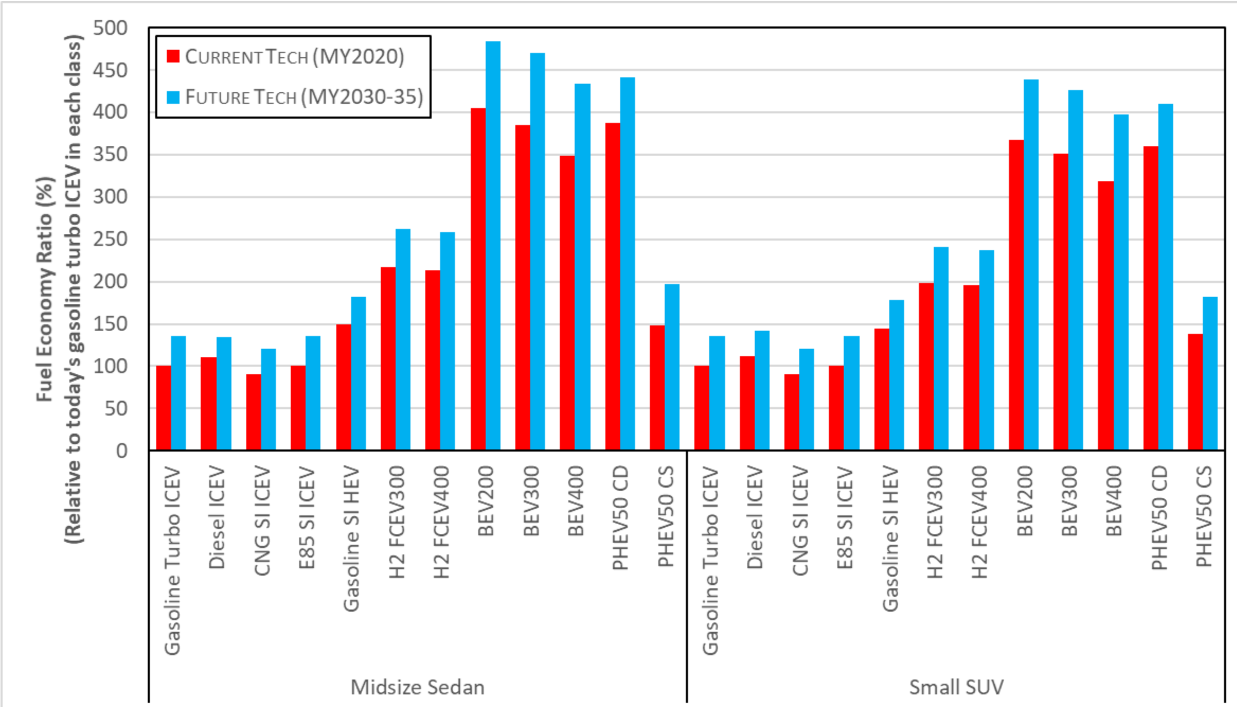

Figure 8. Vehicle fuel economy (mpgge) relative to a CURRENT TECHNOLOGY gasoline turbo ICEV (per class) assuming high powertrain technological progress

6.4. VEHICLE WEIGHT AND COMPOSITION

Vehicle weight and composition (i.e., the mix of materials that comprise the bill of materials) are essential for estimating the energy use and GHG emissions associated with the vehicle manufacturing cycle. We estimate the masses of vehicle components (glider, engine, fuel cell, transmission, energy storage, motor, wheels, etc.) using Autonomie. These masses are then used in GREET, which has bill of materials estimates by component, to determine the associated GHG emissions of the vehicle. Figure 9, Figure 10, Table 26, and Table 27 summarize the weight of components for the different vehicles. As seen in Figure 9 and Figure 10, glider mass is the single largest component.

Vehicle weight decreases by 5% - 24% in the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, depending on the vehicle type for both midsize sedans and small SUVs. As shown in Figure 9 and Figure 10, different weight reductions are expected for different vehicle powertrains. The weight reduction for gasoline ICEVs, E85 ICEVs, CNG ICEVs, and diesel ICEVs is 5–8%; the weight reduction range for HEVs and PHEVs is 7–12%; and FCEVs have a 12% weight reduction. The weights of BEV200s, BEV300s, and BEV400s decrease by 16%, 20%, and 23-24%, respectively. Overall, weight reductions can be achieved in the future compared with current technologies, especially for vehicles with large batteries because the weight reduction in batteries is the most noticeable among the components—ranging from 23% to 53%. Other components with large weight reductions include the ICEV transmission (26%), H_2 FCEV powertrain (23-25%), and glider (9-10%).

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 are assumed to travel 178,102 mi during their lifetime (NHTSA 2006; Francfort 2015).[10]

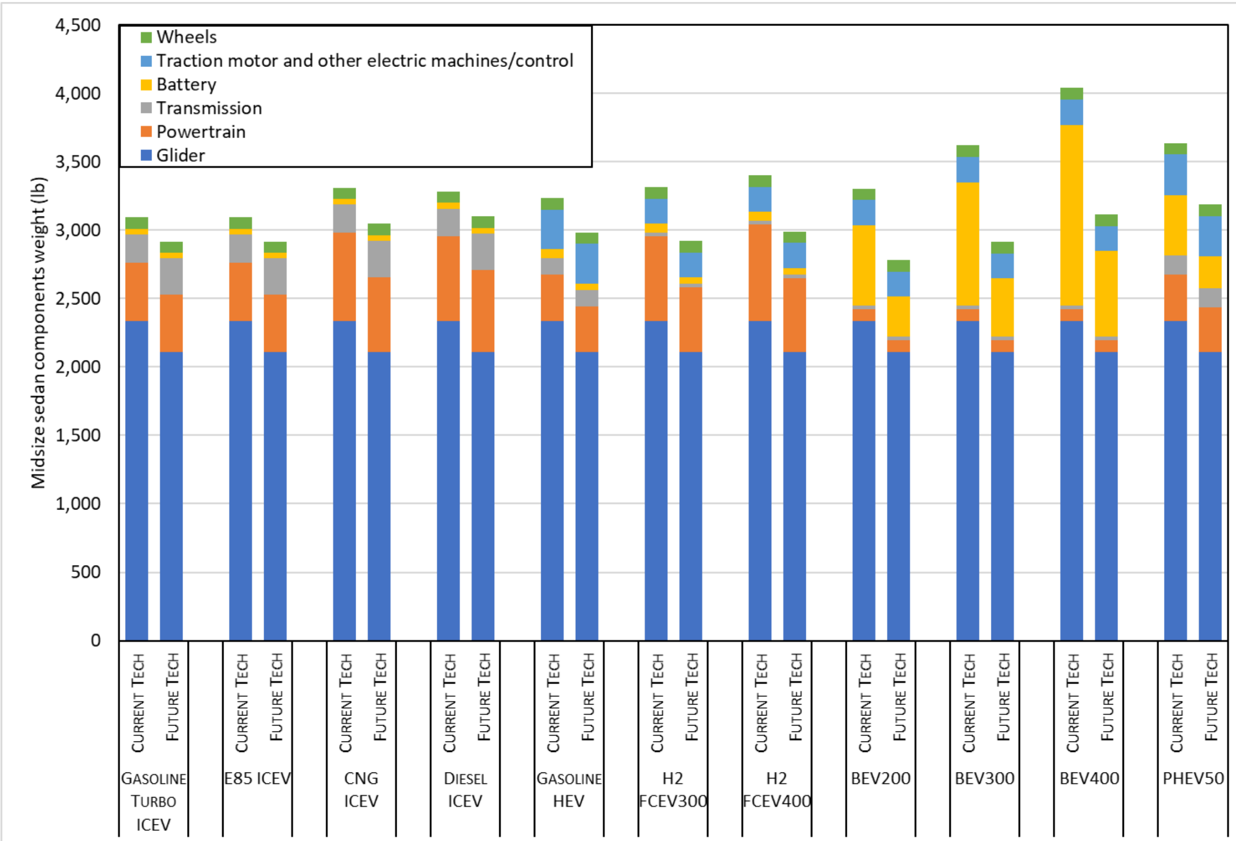

Figure 9. Midsize sedan component weight results (lb)

[10] Lifetime mileages come from the National Highway Traffic Safety Administration and Idaho National Laboratory (NHTSA 2006; Francfort 2015). A detailed discussion of these mileages is given in Section 9.

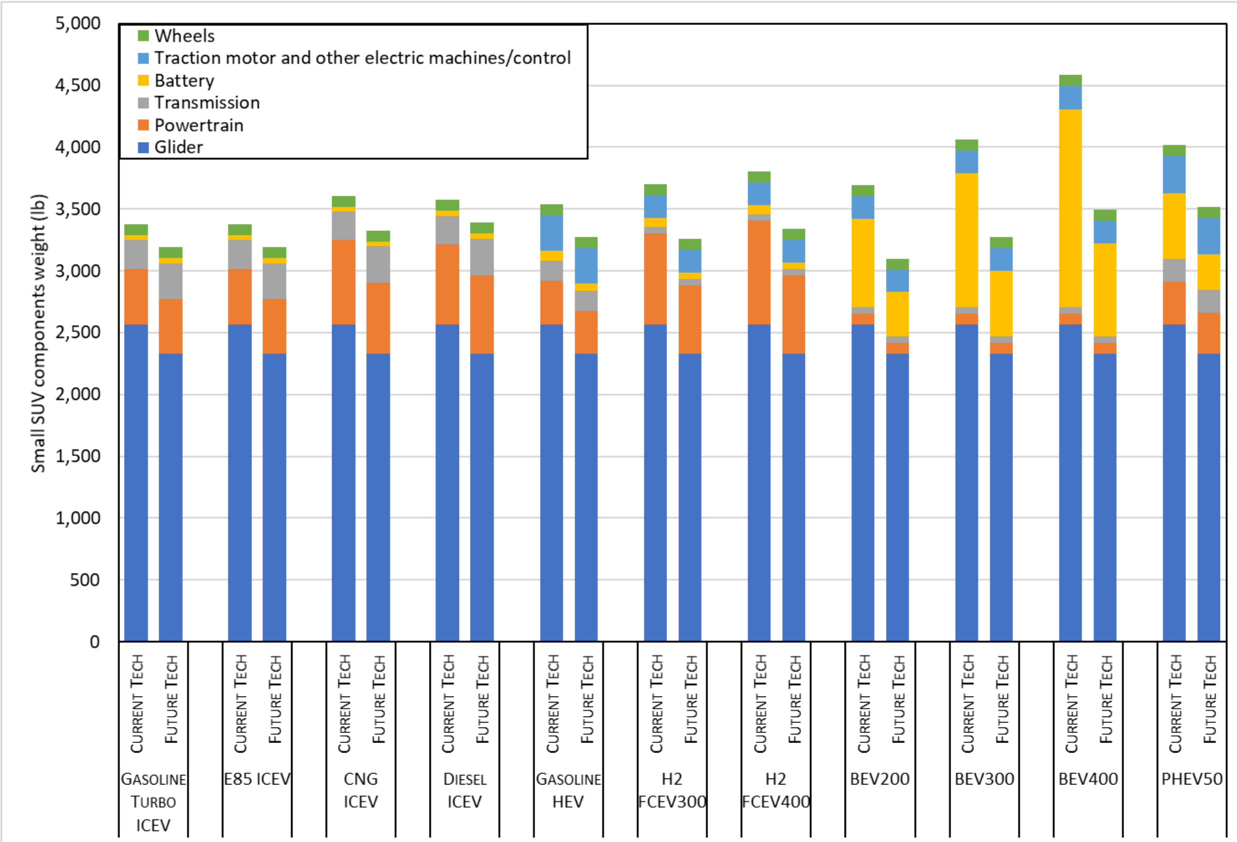

Figure 10. Small SUV component weight results (lb)

Table 26. Sedan weight and composition results

CURRENT TECHNOLOGY	**Gasoline Turbo ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV300**	**H_2 FCEV400**	**BEV200**	**BEV300**	**BEV400**	**PHEV50**
Vehicle weight (lb)	3,093	3,093	3,310	3,285	3,234	3,313	3,402	3,303	3,620	4,039	3,635
Weight composition											
Glider	75.6%	75.6%	70.6%	71.1%	72.3%	70.5%	68.7%	70.8%	64.6%	57.9%	64.3%
Powertrain	13.8%	13.8%	19.5%	18.7%	10.6%	18.7%	20.8%	2.7%	2.4%	2.2%	9.2%
Transmission	6.6%	6.6%	6.2%	6.2%	3.7%	0.8%	0.8%	0.8%	0.7%	0.7%	3.9%
Battery	1.3%	1.3%	1.2%	1.3%	2.0%	1.9%	1.8%	17.7%	24.8%	32.6%	12.2%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	8.9%	5.5%	5.4%	5.5%	5.1%	4.6%	8.1%
Wheels	2.7%	2.7%	2.5%	2.6%	2.6%	2.5%	2.5%	2.5%	2.3%	2.1%	2.3%
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV300**	**H_2 FCEV400**	**BEV200**	**BEV300**	**BEV400**	**PHEV50**
Vehicle weight	2,918	2,918	3,046	3,101	2,982	2,920	2,990	2,782	2,914	3,115	3,187
Weight composition											
Glider	72.2%	72.2%	69.2%	67.9%	70.7%	72.2%	70.5%	75.7%	72.3%	67.7%	66.1%
Powertrain	14.5%	14.5%	18.1%	19.4%	11.2%	16.2%	18.2%	3.2%	3.0%	2.8%	10.2%
Transmission system	9.1%	9.1%	8.7%	8.5%	4.0%	0.9%	0.9%	1.0%	0.9%	0.8%	4.4%
Battery	1.4%	1.4%	1.3%	1.4%	1.6%	1.6%	1.5%	10.6%	14.6%	20.1%	7.4%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	9.7%	6.3%	6.1%	6.5%	6.3%	5.9%	9.2%
Wheels	2.9%	2.9%	2.8%	2.7%	2.8%	2.9%	2.8%	3.0%	2.9%	2.7%	2.6%

Table 27. Small SUV weight and composition results

CURRENT TECHNOLOGY	Gasoline Turbo ICEV	E85 ICEV	CNG ICEV	Diesel ICEV	Gasoline HEV	H_2 FCEV300	H_2 FCEV400	BEV200	BEV300	BEV400	PHEV50
Vehicle weight (lb)	3,377	3,377	3,608	3,576	3,541	3,703	3,807	3,697	4,065	4,588	4,017
Weight composition											
Glider	76.0%	76.0%	71.2%	71.8%	72.5%	69.4%	67.5%	69.5%	63.2%	56.0%	63.9%
Powertrain	13.3%	13.3%	18.9%	18.0%	10.0%	19.9%	22.0%	2.4%	2.2%	1.9%	8.6%
Transmission	6.9%	6.9%	6.4%	6.5%	4.6%	1.4%	1.4%	1.4%	1.3%	1.2%	4.6%
Battery	1.2%	1.2%	1.1%	1.2%	2.2%	1.9%	1.9%	19.3%	26.5%	34.8%	13.3%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	8.2%	5.1%	4.9%	5.1%	4.7%	4.2%	7.4%
Wheels	2.6%	2.6%	2.4%	2.5%	2.5%	2.4%	2.3%	2.4%	2.2%	1.9%	2.2%
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV300**	**H_2 FCEV400**	**BEV200**	**BEV300**	**BEV400**	**PHEV50**
Vehicle weight	3,190	3,190	3,328	3,389	3,276	3,259	3,343	3,100	3,274	3,497	3,519
Weight composition											
Glider	73.0%	73.0%	70.0%	68.7%	71.1%	71.5%	69.7%	75.1%	71.1%	66.6%	66.2%
Powertrain	13.9%	13.9%	17.4%	18.8%	10.6%	16.9%	18.9%	2.8%	2.7%	2.5%	9.5%
Transmission system	9.1%	9.1%	8.7%	8.6%	5.0%	1.6%	1.6%	1.7%	1.6%	1.5%	5.3%
Battery	1.2%	1.2%	1.2%	1.3%	1.8%	1.6%	1.6%	11.6%	16.2%	21.6%	8.1%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	8.9%	5.7%	5.5%	5.9%	5.7%	5.3%	8.4%
Wheels	2.8%	2.8%	2.7%	2.6%	2.7%	2.7%	2.6%	2.8%	2.7%	2.5%	2.5%

6.4.1. Advanced Battery Cost Assumptions

Battery costs play a critical role in determining the overall cost-competitiveness of BEVs. The past decade has seen a dramatic decline in the costs of high-energy Li-ion batteries (Ziegler and Trancik, 2021). As seen in Figure 11, recent assessments of future BEV battery costs by governmental agencies, national laboratories, the National Academy of Sciences, academia, consulting firms, and automakers show this trend is expected to continue in the future. In the present work, we use battery costs from the recent Autonomie model study at Argonne (Islam et al., 2021). For our CURRENT TECHNOLOGY case (MY2020), we use a total pack manufacturing cost of $170/kWh in lab year 2015 (Islam et al., 2021). For our FUTURE TECHNOLOGY case (MY2030-2035), we use high- and low-technological progress values of $70/kWh and $100/kWh, respectively, in lab year 2025 to capture the current uncertainty in future technology costs. As shown in Figure 11, these values are aligned with targets of the U.S. DRIVE research partnership and are broadly representative of the range of cost estimates in the literature.

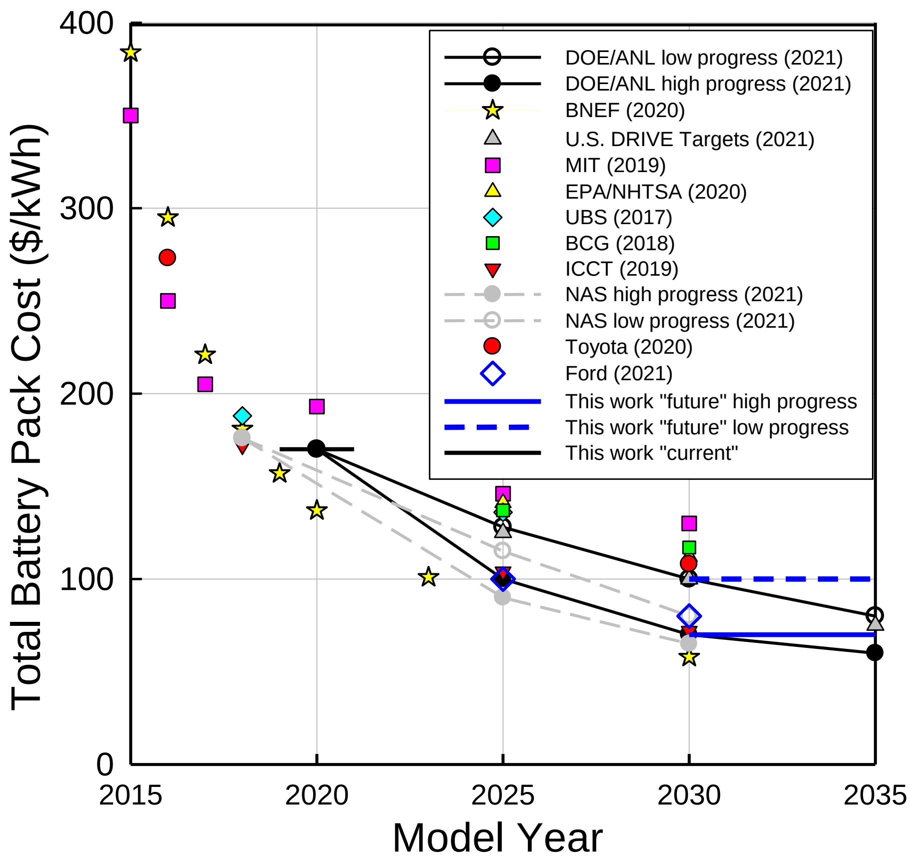

Figure 11. Battery cost estimates from different organizations: DOE/Argonne (Islam et al., 2021); Bloomberg New Energy Finance (2020); U.S. DRIVE (U.S. DRIVE Partnership Plan 2020); Massachusetts Institute of Technology (Ghandi and Paltsev 2019); EPA/NHTSA (2020); UBS (2017); BCG (Mosquet et al. 2018), International Council on Clean Transportation (Lutsey and Nicholas 2019); (National Academies of Sciences 2021); Toyota (Hamza et al. 2020); and Ford (2021). The values are as reported in the different studies and are in 2018-2021 nominal dollars, depending on the source.

6.4.2. Comparison of Battery Cost Assumptions in the 2016 and 2022 C2G reports

By far the largest and the most consequential change in the input assumptions between our previous study and current update is in battery costs for BEVs. Over the past 5-10 years there have been dramatic reductions in the cost of EV batteries, as discussed in Section 6.4.1 and illustrated in Figure 11. Vehicle cost assumptions in both the previous and present studies were taken from assessments at Argonne using the Autonomie model (Moawad et al., 2016; Islam et al., 2021), but battery cost projections have changed significantly over the past five years. For traceability to the original references, we refer to costs below for the 2016 study in 2013$ and for the current study in 2020$.

As described in detail in our previous report (Elgowainy et al., 2016), Autonomie provides estimates of total vehicle manufacturing costs at volume based on a summation of component costs and assembly costs. All vehicle types are modeled using a constant set of performance parameters (acceleration time, top speed, gradeability, etc.). Technical progress results in lower cost and/or improved fuel efficiency. Vehicles are modeled in time steps of five years, and for each vehicle type and for each degree of technical progress, three costs are estimated. This results in a 3×3 matrix for the nine possible combinations of low, medium, and high progress in technology performance and low, medium, and high vehicle cost.

The CURRENT TECHNOLOGY case in our *previous* assessment (Elgowainy et al., 2016) was based on 2010 laboratory year costs reported by Moawad et al. (2016), which were assumed to reflect vehicle MY2015 costs. The 2010 laboratory year manufacturing battery pack cost for the BEV210 was $332.5/kWh (in 2013$).

The CURRENT TECHNOLOGY case in the *present* assessment is based on 2015 laboratory year costs reported by Islam et al. (2021), which are assumed to reflect vehicle MY2020 costs. The 2015 laboratory year manufacturing battery pack cost for the BEV300 is $170/kWh (in 2020$).

The FUTURE TECHNOLOGY case in our *previous* assessment (Elgowainy et al., 2016) was based on 2020 laboratory year costs reported by Moawad et al. (2016), which are assumed to reflect vehicle MY2025 costs. Vehicle costs for the FUTURE TECHNOLOGY case were assumed to be the average of low ($308.75/kWh) and high ($161.5/kWh) vehicle cost progress from the Autonomie medium technology progress case. The average value of $234.5kWh (in 2013$) was assumed for the FUTURE TECHNOLOGY case for MYs2025-2030.

The FUTURE TECHNOLOGY case in our *present* assessment is based on 2025 laboratory year costs reported by Islam et al. (2021), which are assumed to reflect vehicle MY2030 costs. Vehicle costs for the FUTURE TECHNOLOGY case were taken from the high technology progress case in the Autonomie model and are assumed for MYs2030-2035. A battery cost of $70/kWh (2020$) is assumed for 2030-2035 model year BEVs (Islam et al., 2021).

Figure 12 shows the battery pack manufacturing costs in the high and low progress cases from DOE/Argonne used in our previous (Moawad et al., 2016) and present (Islam et al., 2021) studies, with the values assumed in the FUTURE TECHNOLOGY cases in our previous and current work. The DOE/Argonne battery costs in 2015 and 2020 of $332.5/kWh (in 2013$) and $170/kWh (in 2020$) shown in Figure 12 are the values used in the CURRENT TECHNOLOGY cases in the two studies. Figure 12 shows the dramatic decline in current and expected future battery costs for BEVs. It is hard to overstate the importance of the improvements in battery costs on the analysis. The most dramatic illustration is to consider the SUV BEV400 in the present study. For a medium technology progress case in lab year 2025, this vehicle has a total battery pack of 116 kWh. The difference in FUTURE TECHNOLOGY cost assumptions, equating for simplicity 2013$ and 2020$, of $164.5/kWh leads to a reduction of approximately $19,000 in manufacturing costs, and hence retail price of about $29,000 for the future technology SUV BEV400.

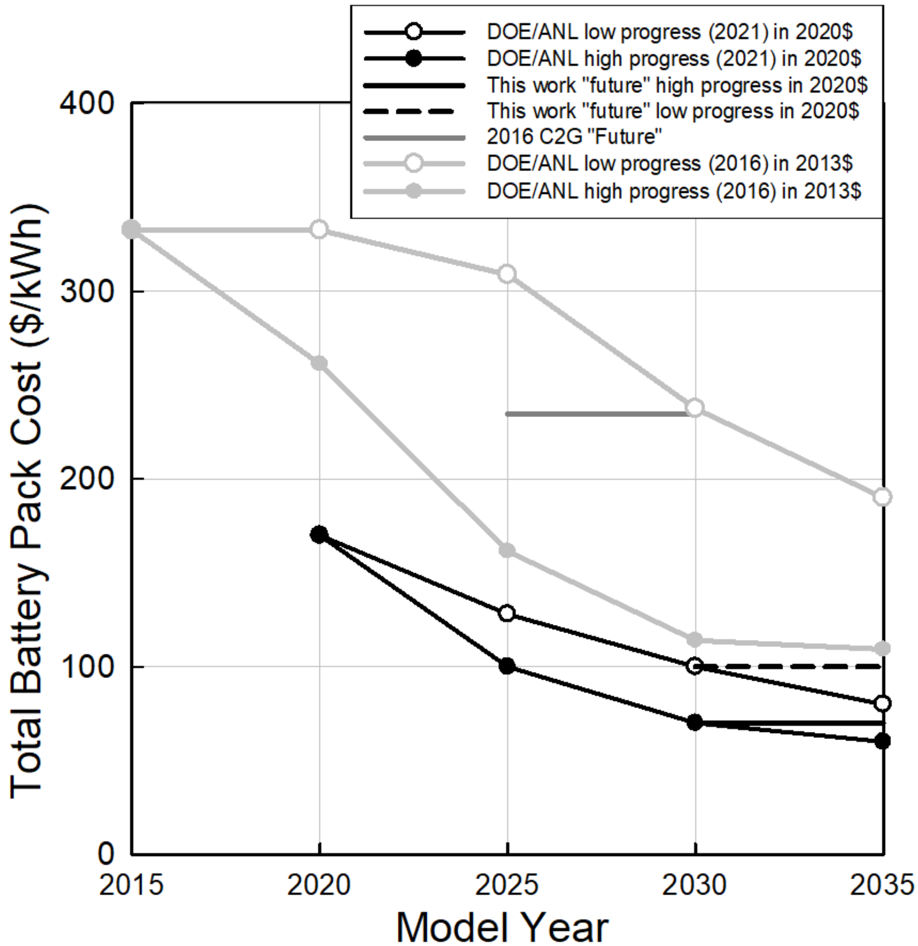

Figure 12. Total battery pack manufacturing cost estimates assuming high (filled symbols) and low (open symbols) progress from DOE/Argonne in 2016 (grey lines, Moawad et al., 2016) and in 2021 (black lines, Islam et al., 2021). FUTURE TECHNOLOGY case values used in our previous C2G study (Elgowainy et al, 2016) and in the current work are shown by horizontal lines. The CURRENT TECHNOLOGY costs used in our previous and current work are shown where the lines converge.

6.5. VEHICLE COST

Autonomie provides estimates of total vehicle manufacturing costs at volume based on a summation of component costs and assembly costs (Islam et. al. 2021). All vehicle types are modeled using a constant set of performance parameters (acceleration time, top speed, gradeability, etc.). Technical progress leads to a lower cost and/or improved fuel efficiency.

Table 28 shows the retail price equivalents (RPEs) for midsize sedans and small SUVs. The detailed costs breakdown and assumptions are provided in Islam et al. 2021. In Table 28, the incremental cost is relative to the conventional gasoline turbo SI ICEV from the CURRENT TECHNOLOGY case. All costs are multiplied by a factor of 1.5 to equate to a RPE with a 50% markup.

As noted in the previous section there has been a major decrease in the battery cost assumptions between our previous report and present assessment. As a result of low battery costs the vehicle costs for the high progress FUTURE TECHNOLOGY cases for the BEV200 and BEV300 are lower than for the CURRENT TECHNOLOGY conventional vehicle as shown in Table 28. Interestingly, this is also the case for the HEV (see Table 28). This reflects the fact that the HEV has a smaller engine than the conventional vehicle and our assumption that engine and transmission costs will increase driven by higher technology costs to meet more stringent fuel economy regulations while battery, electric machine, and power electronics costs will decrease substantially in the high progress case. Additionally, the power split HEV uses a relatively inexpensive Atkinson engine while the conventional vehicle requires an improved, more expensive, engine to reach higher vehicle fuel economy.

Table 28. Vehicle costs (2020$) used in this study from the Autonomie model including 50% markups (Islam et al. 2021)

		CURRENT TECHNOLOGY (2020)		FUTURE TECHNOLOGY (2030-2035)			
Vehicle Technology		Total RPE	Incr. RPE	Total RPE High Progress	Incr. RPE	Total RPE Low Progress	Incr. RPE
Midsize Sedans	Gasoline/E85	$28,630	-	$29,210	$581	$29,920	$1,290
	Diesel	$33,092	$4,462	$30,940	$2,311	$33,426	$4,797
	CNG	$35,420	$6,790	$32,864	$4,235	$35,931	$7,302
	HEV	$32,860	$4,231	$27,870	-$759	$31,062	$2,432
	PHEV50	$38,014	$9,384	$28,990	$361	$33,003	$4,374
	H_2 FCEV300	$49,591	$20,962	$32,697	$4,067	$35,912	$7,283
	H_2 FCEV400	$51,085	$22,456	$33,370	$4,741	$36,895	$8,266
	BEV200	$33,649	$5,020	$24,309	-$4,321	$27,228	-$1,402
	BEV300	$40,824	$12,195	$26,479	-$2,151	$30,720	$2,090
	BEV400	$50,232	$21,603	$29,847	$1,217	$35,596	$6,966
Small SUV	Gasoline/E85	$31,664	-	$31,305	-$359	$32,015	$351
	Diesel	$36,124	$4,459	$33,034	$1,370	$35,519	$3,855
	CNG	$39,466	$7,802	$34,958	$3,294	$38,026	$6,361
	HEV	$36,890	$5,226	$30,516	-$1,149	$33,815	$2,151
	PHEV50	$42,873	$11,208	$31,685	$20	$35,950	$4,285
	H_2 FCEV300	$58,517	$26,853	$36,683	$5,018	$40,656	$8,992
	H_2 FCEV400	$60,358	$28,694	$37,625	$5,961	$42,022	$10,357
	BEV200	$39,920	$8,255	$27,518	-$4,146	$31,062	-$602
	BEV300	$48,229	$16,564	$30,375	-$1,289	$35,280	$3,616
	BEV400	$60,045	$28,381	$34,112	$2,447	$41,359	$9,694

[a] Incremental costs are relative to the CURRENT TECHNOLOGY gasoline turbo ICEV.

6.6. References for Section 6

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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 National Laboratory 2020). The vehicle cycle includes the processes shown in Figure 13. This section describes the calculation of material compositions for the vehicle technologies used in this study and explains the major process assumptions on key material production and vehicle assembly, disposal, and recycling processes. Using this input data, the vehicle manufacturing cycle results are estimated and presented.

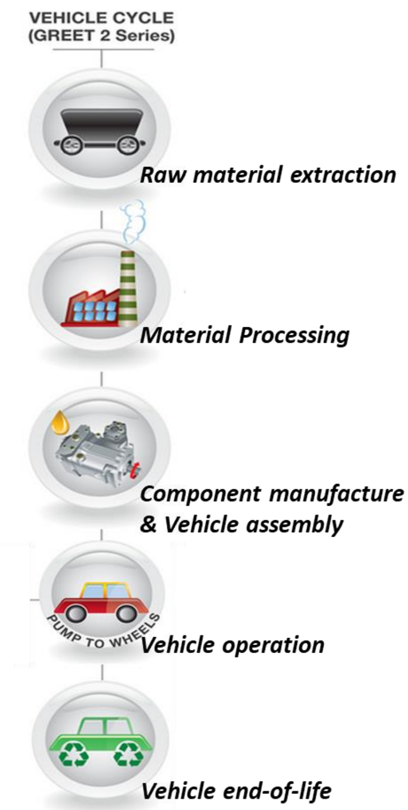

Figure 13. GREET vehicle manufacturing cycle

Figure 14 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. The vehicle manufacturing cycle model considers the material composition (steel, aluminum, iron, plastic, rubber, etc.) of major components. The model includes replacement schedules for components 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 the recycling of scrap materials for reuse. Finally, the model estimates the energy used during raw material recovery and vehicle assembly (e.g., mining through stamping) for vehicle manufacturing cycle simulations. Currently, for most of the raw and processed materials in GREET2, energy use and emissions from transportation between processes are not taken into account. However, the impact of materials transportation on C2G GHG emissions is negligible.

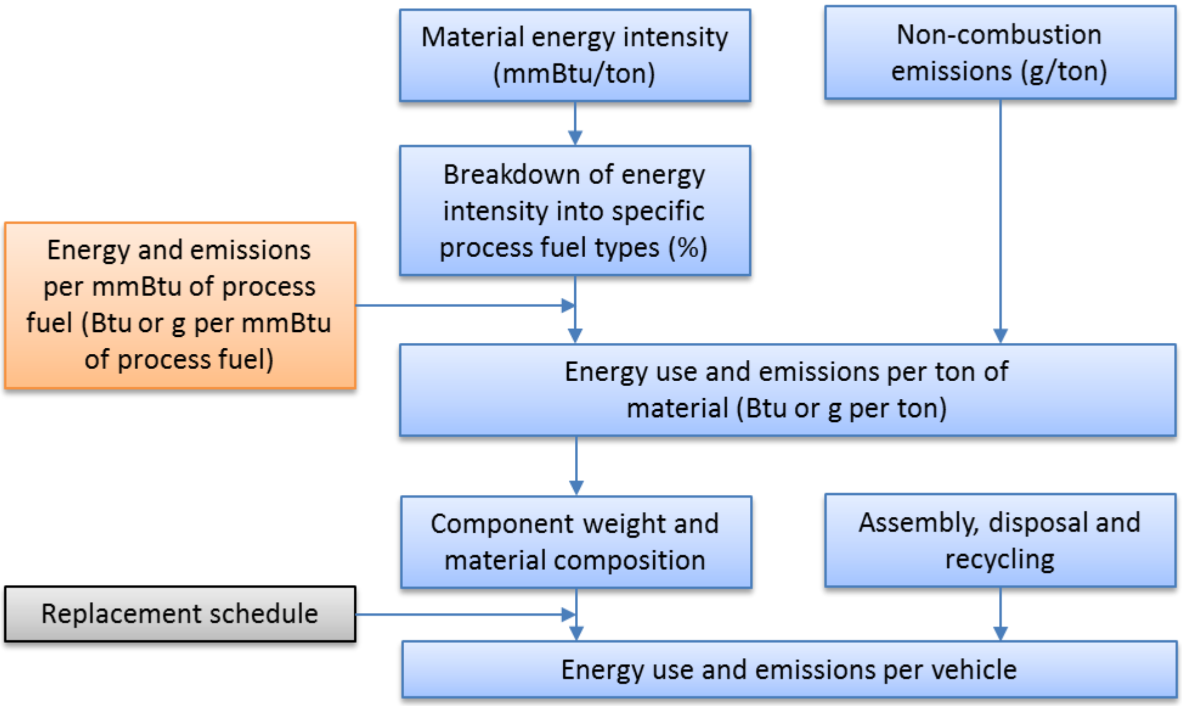

Figure 14. Process for GREET vehicle manufacturing cycle analysis

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 subcomponents, such as the body, exterior, and chassis, with weld blanks and fasteners included. Similarly, the powertrain consists of the engine, engine fuel storage system, power train thermal, fuel cell stack, fuel cell auxiliaries, exhaust, powertrain electrical, emission control electronics, weld blanks, and fasteners. We use the subcomponent weight distribution defined in GREET and provided in Table 29 and Table 30. The development of subcomponent weight distributions, documented in Burnham (2012) and Winjobi and Kelly (2020), are based largely on the Automotive System Cost Model (ASCM) developed by IBIS Associates and Oak Ridge National Laboratory, as well as available data from automotive teardowns through A2Mac1. The 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. A2Mac1 is a global organization that conducts detailed automotive teardowns to identify mass and materials associated with vehicle components (among other attributes). Additional sources for subcomponent weights include vehicle simulation results using the Powertrain System Analysis Toolkit (Moawad et al. 2011), Carlson (2004), and other sources (Cooper 2004).

Vehicle components and subcomponents contain more than one material, and their material compositions need to be estimated. Table 31 and Table 32 list the material compositions for the vehicle components and subcomponents for midsize sedans and small SUVs, respectively, except for batteries, which are estimated in Winjobi and Kelly (2020), Kelly et al. (2016), and Burnham (2012). Note that, with the exception of the 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 29. Subcomponent weight distribution for midsize sedans (%)

Component	ICEV	HEV	PHEV	BEV	FCEV	Source
Glider (chassis, body, etc.)						
Body	47	47	47	47	47	Kelly & Winjobi (2020)
Exterior	4	4	4	4	4	Kelly & Winjobi (2020)
Interior	17	17	17	17	17	Kelly & Winjobi (2020)
Chassis	32	32	32	32	32	Kelly & Winjobi (2020)
Powertrain						
Engine	54	54	54	–	–	Kelly & Winjobi (2020)
Fuel storage system	8	8	8	–	–	Kelly & Winjobi (2020)
Exhaust	13	13	13	–	–	Kelly & Winjobi (2020)
Powertrain electrical	17	17	17	–	–	Kelly & Winjobi (2020)
Powertrain thermal	7	7	7	–	–	Kelly & Winjobi (2020)
Fuel cell stack and BOP	–	–	–	–	49	Kelly et al. (2016)
Hydrogen storage and BOP	–	–	–	–	51	Kelly et al. (2016)

Table 30. Subcomponent weight distribution for small SUVs (%)

Component	ICEV	HEV	PHEV	BEV	FCEV	Source
Glider (chassis, body, etc.)						
Body	45	45	45	45	45	Kelly & Winjobi (2020)
Exterior	4	4	4	4	4	Kelly & Winjobi (2020)
Interior	17	17	17	17	17	Kelly & Winjobi (2020)
Chassis	34	34	34	34	34	Kelly & Winjobi (2020)
Powertrain						
Engine	53	53	53	–	–	Kelly & Winjobi (2020)
Fuel storage system	8	8	8	–	–	Kelly & Winjobi (2020)
Exhaust	13	13	13	–	–	Kelly & Winjobi (2020)
Powertrain electrical	17	17	17	–	−	Kelly & Winjobi (2020)
Powertrain thermal	8	8	8	–	−	Kelly & Winjobi (2020)
Fuel cell stack and BOP	−	−	−	–	47	Kelly et al. (2016)
Hydrogen storage and BOP	−	−	−	–	53	Kelly et al. (2016)

Even though material compositions are consistent at a component or subcomponent level, 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 33 and Table 34 present material composition aggregated by component (excluding batteries) for midsize sedans and small SUVs, respectively. Steel accounts for the largest share of vehicle weight throughout all vehicle technologies (52–63%), followed by plastic (13–16%) and cast aluminum (5–10%). Wrought aluminum, accounting for 1–6% and 2–5% of vehicle weight for midsize sedans and small SUVs, respectively, is a key material contributing to vehicle manufacturing GHG emissions due to its high GHG intensity, even though its share is smaller than steel, plastic, and cast aluminum. Stainless steel and carbon fiber reinforced plastic (CFRP) account for 4–5% and 4-6% of FCEV total weight, respectively. CFRP production is GHG intensive. Copper (2–5%), glass (2–3%), and rubber (3-6%) are also widely used in vehicles. Other minor materials include organics, 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 35 presents the battery material compositions for lead-acid and Li-ion batteries, based on Cuenca et al. (1998) and Winjobi et al (2020) for Li-ion batteries, using Argonne's Battery Performance and Cost (BatPaC) model (Nelson et al. 2019).

The BatPaC model (Nelson et al. 2019) 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 several chemistries, as described below. A polymeric binder 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.

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)
    - NMC111-G (called NMC333-G in BatPac)
    - NMC532-G
    - NMC622-G
    - NMC811-G
- Lithium iron phosphate with a graphite electrode (LFP-G)
- Lithium manganese spinel with a titanium dioxide electrode (LMO-LTO)
- 50% lithium nickel manganese cobalt oxide (NMC532) and 50% lithium manganese oxide spinel with a graphite electrode (NMC532-50% LMO-G)
- Lithium manganese oxide spinel with a graphite electrode (LMO-G).

NMC111-G is used as the CURRENT TECHNOLOGY case for the HEV, FCEV, PHEV. and BEV models for each vehicle type. NMC111-G is the default battery chemistry in GREET, because it is relatively cheap with a high energy density (Winjobi et al. 2020). NMC111 means that this is a cathode with equal molar ratios of Ni to Co to Mn. In fact, the NMCxyz nomenclature is common, referencing the more complete cathode chemistry $LiN_xCo_yMn_z$, where the numerical values (xyz) describe the molar ratios for each element. NMC111-G batteries are also widely used in current HEVs, PHEVs, and BEVs. However, as energy density continues to advance, the FUTURE Technology condition utilizes NMC811-G batteries for BEVs, as these can facilitate higher energy density. Future developments may seek to further reduce or eliminate the use of cobalt or nickel to ease environmental burdens and stabilize supply chains, which have been identified as challenges for these batteries.

Table 31. Material composition of components and subcomponents for midsize sedans, except for battery (%)

Component	Steel	Wrought Aluminum	Cast Aluminum	Copper	Magnesium	GFRP	Glass	Average Plastic[a]	Rubber	Stainless Steel	CFRP	Cast Iron	Others	Source
Glider (chassis, body, etc.)														
Body	79	3	–	–	–	–	6	10	1	–	–	–	–	Winjobi and Kelly (2020)
Exterior	29	2	–	8	–	7	8	43	2	–	–	–	–	Winjobi and Kelly (2020)
Interior	33	3	1	4	–	1	–	46	5	–	–	–	–	Winjobi and Kelly (2020)
Chassis	81	2	3	2	–	–	–	3	8	–	–	–	–	Winjobi and Kelly (2020)
Powertrain														
Engine	44	5	39	2	–	3	–	5	2	–	–	–	–	Winjobi and Kelly (2020)
Engine fuel storage system	30	–	–	3	–	–	–	63	3	–	–	–	–	Winjobi and Kelly (2020)
Exhaust	92	2	4	–	–	–	–	–	1	–	–	–	–	Winjobi and Kelly (2020)
Powertrain electrical	17	2	3	28	–	–	–	50	1	–	–	–	–	Winjobi and Kelly (2020)
Powertrain thermal	17	21	7	5	–	9	–	33	9	–	–	–	–	Winjobi and Kelly (2020)
Fuel cell stack & BOP	19	17	–	2	–	3	–	17	6	31	–	–	6	Kelly et al. (2016)
H_2 storage and BOP	9	–	–	–	–	4	–	8	–	8	66	–	4	Kelly et al. (2016)
Transmission														
ICEV	66	5	23	2	–	1	–	3	–	–	–	–	–	Winjobi and Kelly (2020)
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	–	–	–	–	–	–	–	–	–	–	Winjobi and Kelly (2020)
Tires	33	–	–	–	–	–	–	67	–	–	–	–	–	Muir (2005); Argonne assumptions

[a] See Table 39 for the share of average plastic in a vehicle

Table 32. Material composition of components and subcomponents for small SUVs, except for battery (%)

Component	Steel	Wrought Aluminum	Cast Aluminum	Copper	Magnesium	GFRP	Glass	Average Plastic[a]	Rubber	Stainless Steel	CFRP	Cast Iron	Others	Source
Glider (chassis, body, etc.)														
Body	78	3	–	1	–	–	6	12	1	–	–	–	–	Winjobi and Kelly (2020)
Exterior	21	9	1	12	–	4	9	42	2	–	–	–	–	Winjobi and Kelly (2020)
Interior	40	2	1	4	–	1	1	45	4	–	–	–	2	Winjobi and Kelly (2020)
Chassis	78	2	5	2	–	1	–	4	8	–	–	–	–	Winjobi and Kelly (2020)
Powertrain														
Engine	38	4	40	3	–	3	–	8	2	–	–	1	–	Winjobi and Kelly (2020)
Engine fuel storage system	20	3	–	3	–	1	–	70	2	–	–	–	–	Winjobi and Kelly (2020)
Exhaust	77	2	19	–	–	–	–	1	1	–	–	–	–	Winjobi and Kelly (2020)
Powertrain electrical	10	1	2	31	–	2	–	53	1	–	–	–	–	Winjobi and Kelly (2020)
Powertrain thermal	16	21	4	4	–	6	–	38	11	–	–	–	–	Winjobi and Kelly (2020)
Fuel cell stack & BOP	19	17	–	2	–	3	–	17	6	31	–	–	6	Kelly et al. (2016)
H_2 storage and BOP	9	–	–	–	–	4	–	8	–	8	66	–	4	Kelly et al. (2016)
Transmission														
ICEV	67	4	21	3	–	1	–	5	–	–	–	–	–	Winjobi and Kelly (2020)
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	–	–	–	–	–	–	–	–	–	–	Winjobi and Kelly (2020)
Tires	33	–	–	–	–	–	–	67	–	–	–	–	–	Muir (2005); Argonne assumptions

[a] See Table 39 for the share of average plastic in a vehicle

Table 33. Material composition for midsize sedans aggregated by component, except for battery (%)

Current Technology	**Gasoline ICEV**	**E85 ICEV**	**Diesel ICEV**	**CNG**	**HEV**	**FCEV 300**	**FCEV 400**	**PHEV50**	**BEV200**	**BEV300**	**BEV400**
Steel	60	60	59	59	60	54	53	61	63	63	63
Cast iron	2	2	2	2	3	-	-	2	-	-	-
Wrought aluminum	5	5	5	5	3	4	4	3	2	2	2
Cast aluminum	8	8	9	9	10	7	7	10	8	8	8
Copper	2	2	3	3	4	3	3	5	4	4	4
Glass	2	2	2	2	2	2	2	2	3	3	3
Average plastic	15	15	15	15	13	14	14	13	15	15	15
Rubber	4	4	4	4	3	4	4	3	4	4	4
Stainless steel	-	-	-	-	-	4	4	-	-	-	-
CFRP	-	-	-	-	-	4	6	-	-	-	-
Others	1	1	1	1	1	3	3	1	1	1	1
Future Technology	**Gasoline ICEV**	**E85 ICEV**	**Diesel ICEV**	**CNG**	**HEV**	**FCEV 300**	**FCEV 400**	**PHEV50**	**BEV200**	**BEV300**	**BEV400**
Steel	59	59	58	58	60	55	54	60	62	62	62
Cast iron	3	3	3	3	3	-	-	3	-	-	-
Wrought aluminum	5	5	5	5	3	4	4	3	2	2	2
Cast aluminum	8	8	9	9	10	7	7	10	8	9	9
Copper	2	2	3	2	5	3	3	5	4	4	4
Glass	2	2	2	2	2	2	2	2	3	3	3
Average plastic	15	15	15	15	13	14	14	13	15	15	15
Rubber	4	4	4	4	3	4	4	3	4	4	4
Stainless steel	-	-	-	-	-	3	4	-	-	-	-
CFRP	-	-	-	-	-	4	5	-	-	-	-
Others	1	1	1	1	1	3	3	1	1	1	1

Table 34. Material composition for small SUVs aggregated by component, except for battery (%)

CURRENT TECHNOLOGY	Gasoline ICEV	E85 ICEV	Diesel ICEV	CNG	HEV	FCEV 300	FCEV 400	PHEV50	BEV200	BEV300	BEV400
Steel	59	59	58	57	60	53	52	61	62	62	62
Cast iron	2	2	2	2	2	-	-	2	-	-	-
Wrought aluminum	5	5	5	5	3	4	4	3	3	3	3
Cast aluminum	6	6	7	7	8	5	5	8	6	6	6
Copper	3	3	3	3	5	3	3	5	4	4	4
Glass	2	2	2	2	2	2	2	2	3	3	3
Average plastic	16	16	16	16	13	15	14	13	15	15	15
Rubber	6	6	6	6	5	6	6	5	6	6	6
Stainless steel	-	-	-	-	-	4	5	-	-	-	-
CFRP	-	-	-	-	-	5	6	-	-	-	-
Others	1	1	1	1	1	3	3	1	1	1	1
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**Diesel ICEV**	**CNG**	**HEV**	**FCEV 300**	**FCEV 400**	**PHEV50**	**BEV200**	**BEV300**	**BEV400**
Steel	58	58	57	57	60	55	54	60	62	62	62
Cast iron	3	3	3	3	3	-	-	2	-	-	-
Wrought aluminum	5	5	5	5	3	4	4	3	3	3	3
Cast aluminum	6	6	7	7	8	5	5	8	6	6	6
Copper	3	3	3	3	5	3	3	5	4	4	4
Glass	2	2	2	2	2	2	2	2	3	3	3
Average plastic	16	16	16	16	13	15	14	13	15	15	15
Rubber	6	6	6	6	5	6	6	5	6	6	6
Stainless steel	-	-	-	-	-	4	4	-	-	-	-
CFRP	-	-	-	-	-	4	6	-	-	-	-
Others	1	1	1	1	1	3	3	1	1	1	1

Table 35. Material composition of batteries (%)

Material	Lead-Acid Battery	Li-ion Battery			
		Gasoline HEVs, H_2 FCEVs (NMC111)	PHEV50 (NMC111)	CURRENT TECH EVs (NMC111)	FUTURE TECH EVs (NMC811)
Lead	69	–	–	–	–
Active material	–	19	31	38	32
Wrought aluminum	–	18	16	17	18
Copper	–	18	12	7	7
Graphite/carbon	–	10	16	20	24
Electronic parts	–	15	5	2	2
Plastic: polypropylene	6	2	1	1	1
Plastic: polyethylene	–	0	0	0	0
Plastic: polyethylene terephthalate	–	0	0	0	0
Electrolyte: ethylene carbonate	–	4	5	4	4
Electrolyte: dimethyl carbonate	–	4	5	4	4
Electrolyte: $LiPF_6$	–	1	2	1	1
Steel	–	2	1	1	1
Coolant: glycol	–	4	4	3	3
Binder	–	1	1	2	2
Water	14	–	–	–	–
Sulfuric acid	8	–	–	–	–
Fiberglass	2	–	–	–	–
Others	1	–	–	–	–

7.3. KEY MATERIAL PATHWAYS FOR VEHICLE PRODUCTION

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 vehicle production. For each material, this study characterizes raw material sources, production and fabrication processes, and recycling processes for major materials in the vehicle production pathway, 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.

It is important to note that the analysis of the material production pathway in the GREET model is based on the best available data that can be openly cited. In general, the material production pathway does not have temporal changes in process or resource efficiencies. As a result, estimates will vary over time depending on changes associated with energy inputs (i.e., the upstream processes for obtaining energy). Therefore, changes in GHG emissions over time associated with materials in this model are associated with changes to electricity grids. To examine the effects of changes in material processes, we conduct sensitivity analyses in Appendix C that considers the use of “green” steel (which utilizes hydrogen in production), and we further examine the effect of major grid decarbonization on all materials.

7.3.1. Steel Production Pathways

Figure 15 presents the steel production flowchart modeled in GREET. The first step in steelmaking is extracting iron ore (usually taconite in the U.S.), 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 byproducts, 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 byproduct chemical plant are a particular concern. Coal dust may be released during oven charging.

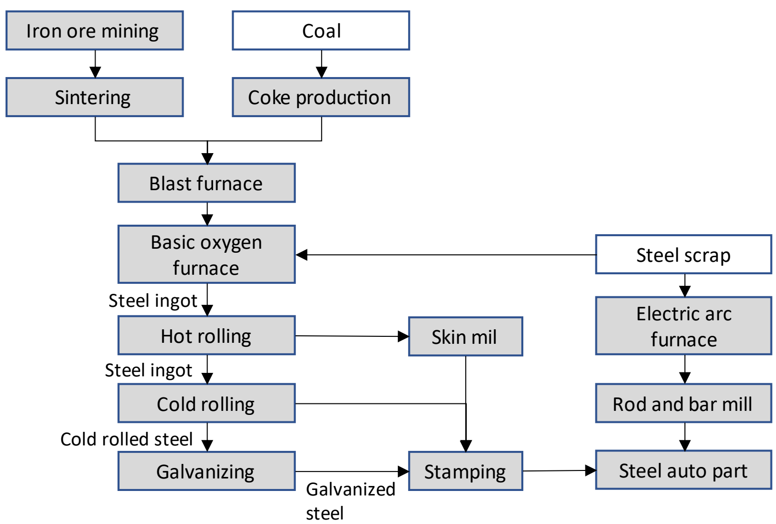

Figure 15. Steel production steps

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 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. Third, 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 either 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 36 lists the process assumptions for steel production, including fuel consumption, input material, and non-combustion emissions. Note that intermediate products can be used as inputs 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.

Table 36. 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	–	–	–	–	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	0.86	4.99	1.08	0.54
Intermediate fuel														
Coke	MMBtu	–	–	0.15	10.07	–	–	–	–	–	–	0.17	–	–
Blast furnace gas	MMBtu	–	0.36	–	–	0.33	0.03	0.03	0.25	0.18	–	–	–	–
Coke oven gas	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 steel product	ton	–	–	–	–	–	1.03	1.02	1.05	1.00	1.00	–	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: Dai et al. (2017a)

[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.

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 37 summarizes the process assumptions for cast iron production.

Table 37. 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] Source: Burnham et al. (2006); Cuenca (2005)

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

7.3.3. Aluminum Production Pathway

Figure 16 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).

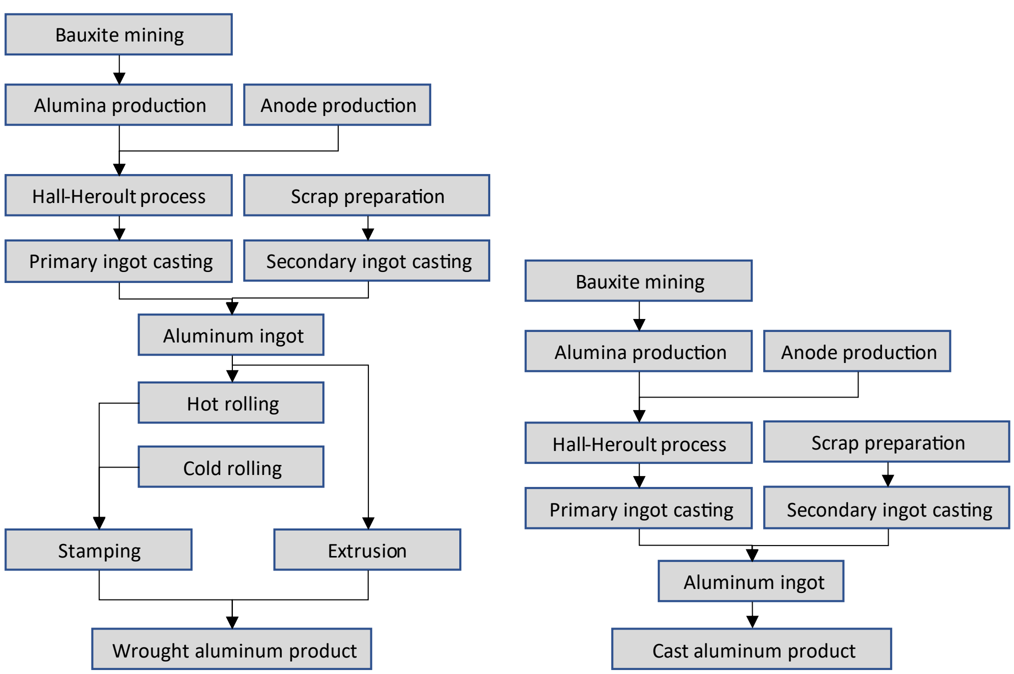

Figure 16. Wrought and cast aluminum production steps

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 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 the large-scale recycling of aluminum automotive parts, 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 38 lists the input fuel and material and non-combustion emissions associated with the aluminum production pathway. Dai et al. (2015a) utilized aluminum production assumptions based on 2011 North American industry data (Aluminum Association 2013) to develop aluminum production energy and emissions profiles, which have been integrated into GREET since 2015. Cast aluminum production assumptions, specifically those for shape casting and machining are taken from Sullivan et al. (2010).

Table 38. Process assumptions for aluminum production (per ton finished aluminum product)

		Virgin Aluminum					Recycled Aluminum			Wrought Aluminum Production				Cast Aluminum Production	
Input	**Unit**	**Bauxite Mining[a]**	**Alumina Production[a]**	**Anode Production[a]**	**Hall-Héroult Process[a]**	**Primary Ingot Casting[a]**	**Wrought Al Scrap Preparation[a]**	**Cast Al Scrap Preparation[a]**	**Secondary Ingot Casting[a]**	**Hot Rolling[a]**	**Cold Rolling[a]**	**Stamping[a]**	**Extrusion[a]**	**Shape Casting[b]**	**Machining[b]**
Fuel															
Residual oil	MMBtu	0.21	2.94	0.52	-	0.11	-	-	-	-	-	-	-	-	-
Diesel	MMBtu	0.35	-	0.10	-	0.03	-	-	-	-	-	-	-	-	-
Gasoline	MMBtu	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NG	MMBtu	-	12.91	0.71	-	0.66	0.75	0.75	4.12	3.28	1.89	-	5.29	-	-
Coal	MMBtu	-	1.34	-	-	-	-	-	-	-	-	-	-	-	-
LPG	MMBtu	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity	MMBtu	0.02	0.64	0.16	46.78	0.21	0.35	0.35	0.34	0.35	1.13	0.86	0.61	0.86	0.54
Material															
NaOH (50%)	ton	-	0.306	-	-	-	-	-	0.0004	0.00002	0.0001	-	0.008	-	-
Lime	ton	-	0.078	-	-	-	0.001	0.001	0.004	0.0002	0.0003	-	-	-	-
Pet coke input	ton	-	-	0.286	-	-	-	-	-	-	-	-	-	-	-
Coke input	ton	-	-	0.063	0.006	-	-	-	-	-	-	-	-	-	-
Steel Sheet Part	ton	-	-	0.003	0.004	-	-	-	0.0001	0.00001	0.0002	-	0.001	-	-
Primary Al ingot	ton	-	-	-	-	-	-	-	0.080	-	-	-	-	-	-
Non-combustion emissions															
CF4	g	-	-	-	69.764	-	-	-	-	-	-	-	-	-	-
C2F6	g	-	-	-	9.616	-	-	-	-	-	-	-	-	-	-
CO2	ton	-	-	0.042	1.392	-	-	-	0.00001	-	-	-	-	-	-

[a] Source: Dai et al. (2015a)

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

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) provide the percent by weight of 16 types of plastic in an average family sedan, shown in Table 39. The types of plastic include 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 39 lists the resin production energy for the 16 plastic types based on Keoleian et al. (2012), which analyzed data from Franklin Associates (2011, 2001), Plastics Europe (2010), Sullivan et al. (2010), and Brown et al. (1996).

Table 39. 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]	109.1	–	70

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

[b] Source: Iyer et al. (2021), 0.95 and 2.33 tons of ammonia and propylene, respectively, are also needed

Table 40 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 semifinished 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 40 also provides the weight distribution of transformation processes for each resin used in a vehicle, based on Sullivan et al. (1998). For example, the average HDPE products in a vehicle consist of HDPE from injection molding (67%), compression molding (24%), and extrusion (9%).

Table 40. 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 40, 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 graphene, which merge to form a tubular filament or “fiber.” The fibers are then enhanced to make high-strength carbon through a heat treatment. The high cost of carbon fiber is primarily attributed to the complexity of the production process. In addition to its high cost, carbon fiber production is very energy-intensive (Iyer and Kelly 2021).

7.3.5. Li-ion Battery Production Pathways

Figure 17 presents the components and processes with material and energy flows in GREET for Li-ion battery production using lithium nickel manganese cobalt oxide (NMC) cathode material, which consists of five major material pathways: cathode active materials (NMC), anode active material (graphite), binder (polyvinylidene fluoride (PVDF)), electrolyte, and the battery management system (BMS).

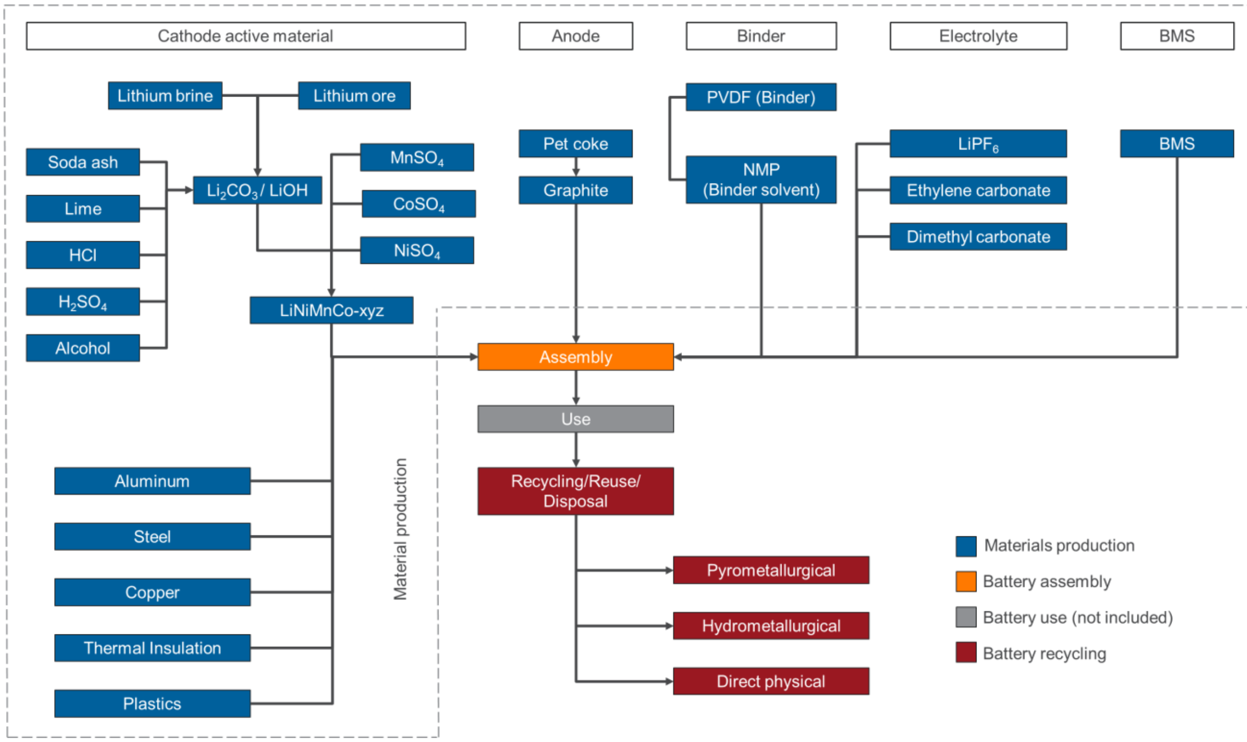

Figure 17. Li-ion battery production material and energy flows in GREET, modified from (Dunn et al. 2014b)

We assume CURRENT TECHNOLOGY vehicles use NMC111 batteries and FUTURE TECHNOLOGY vehicles use NMC811 batteries. The trailing numbers in the cathode identification indicate the stoichiometric relationship between nickel, manganese, and cobalt, respectively. A raw material for NMC111 production is lithium carbonate (Li_2CO_3), which can be produced from concentrated lithium brine, while NMC811 is produced from lithium hydroxide monohydrate ($LiOH.H_2O$, often shortened to LiOH). LiOH can be produced from the further processing of Li_2CO_3. Sources of lithium include brine, pegmatites, or sedimentary rocks (Gruber et al. 2011). Brine and spodumene ore are currently the most common source of lithium, much of it originating from Australia (spodumene) and the Salar de Atacama (brine) (Jaskula 2020). Dunn et al. (2014b) developed GREET's battery LCA module based on data for one operation in Chile and one in Nevada. We assume lithium from Chilean lithium brine since this pathway represents the largest share of Li-ion batteries used in the U.S. 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). To obtain LiOH, Li_2CO_3 is reacted with $CaCO_3$ to produce an aqueous solution of lithium hydroxide that is subsequently evaporated, and dried to produce LiOH (Dai and Winjobi 2019).

In addition to Li_2CO_3 and LiOH, nickel sulfate ($NiSO_4$), manganese sulfate ($MnSO_4$) and cobalt sulfate ($CoSO_4$) are needed for NMC production. $NiSO_4$ is produced from nickel derived from both sulfide and laterite ores, as documented in Wang et al. (2020a). Manganese sulfate is produced by reacting sulfuric acid with Mn ore (Wang 2020b). $CoSO_4$ production consists of cobalt ore mining, processing, and conversion to $CoSO_4$, as described in Dai et al. (2018a).

Cathode precursors for NMC111 and NMC811 are required prior to conversion to cathode materials. The precursor for NMC111 is nickel manganese cobalt hydroxide $NMC111(OH)_2$, whereas for NMC811, it is nickel manganese cobalt hydroxide $NMC811(OH)_2$. Precursor production is similar for NMC111 and 811, the metal sulfates, $NiSO_4$, $MnSO_4$, and $CoSO_4$ are dissolved and mixed (in appropriate proportions) in a tank reactor. Once dissolved and mixed, NaOH and NH_4OH are added to the solution and heated. Once the $NMC(OH)_2$ precipitates, it is filtered, washed, and dried for use (Dai et al. 2018b).

Finally, for NMC111, cathode material is produced by mixing Li_2CO_3 with $NMC111(OH)_2$ and then calcined in multiple stages with heat supplied by electricity (Dai et al. 2018b). Dai et al. (2018b) describe that a similar process is used to produce NMC811, but that LiOH is combined with $NMC811(OH)_2$ to be calcined in multiple stages with electrical heating.

Synthetic graphite anodes are assumed for use in Li-ion batteries. Dunn et al. described the production of synthetic graphite from petroleum coke and tar pitch (2015). 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 (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 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. 2019). 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 41 provides the key assumptions for the Li-ion battery production pathway developed in Dunn et al. (2014b) from an extensive literature review on Li-ion battery materials, as described above. Since Li_2CO_3 is produced in Chile, the 2018 Chilean electricity mix is used for the processes: 35.7% coal, 28.7% hydropower, 15.6% NG, 7.3% biofuels, 1.7% oil, 11% combined from wind and solar PV (IEA 2018).

Table 41. Li-ion battery production process assumptions

Input or Emission	Unit	Active Material (NMC111/811) Production							Other Battery Material Production						
		Li_2CO_3 and LiOH Production (Chile)													
		Conc. Li Brine	Li_2CO_3	LiOH	NNMC111(OH)2	NMC811(OH)2)	NNMC111	NNMC811	Graphite	PVDF (Binder)	$LiPF_6$	Ethylene Carbonate	Dimethyl Carbonate	N-Methyl-2-pyrrolidone (Binder Solvent)	BMS
Input fuel															
Residual oil	MMBtu/ton	–	–	–	–	–	–	–	–	0.84	0.37	–	–	–	–
Diesel	MMBtu/ton	0.13	5.99	–	–	–	–	–	–	–	–	–	–	–	–
NG	MMBtu/ton	–	2.26	9.70	38.62	38.62	–	–	5.15	11.97	–	0.22	1.27	1.73	84.05
Coal	MMBtu/ton	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Electricity	MMBtu/ton	–	1.75	–	–	–	21.67	24.76	13.93	8.19	72.64	0.04	0.09	1.02	120.95
Input material															
Soda ash	ton/ton	–	2.48	–	–	–	–	–	–	–	–	–	–	–	–
Conc. Li brine	ton/ton	–	5.45	–	–	–	–	–	–	–	–	–	–	–	–
Li_2CO_3	ton/ton	–	–	1.54	–	–	0.38	–	–	–	–	–	–	–	–
Lime	ton/ton	–	–	1.17	–	–	–	–	–	–	–	–	–	–	–
LiOH		–	–	–	–	–	–	0.38	–	–	–	–	–	–	–
$NiSO_4$	ton/ton	–	–	–	0.56	1.34	–	–	–	–	–	–	–	–	–
$CoSO_4$	ton/ton	–	–	–	0.56	0.17	–	–	–	–	–	–	–	–	–
$MnSO_4$	ton/ton	–	–	–	0.55	0.16	–	–	–	–	–	–	–	–	–
NaOH	ton/ton	–	–	–	0.89	0.89	–	–	–	–	–	–	–	–	–
NH_4OH	ton/ton	–	–	–	0.12	0.12	–	–	–	–	–	–	–	–	–
$NMC111(OH)_2$	ton/ton	–	–	–	–	–	0.95	–	–	–	–	–	–	–	–
$NMC811(OH)_2$	ton/ton	–	–	–	–	–	–	0.95	–	–	–	–	–	–	–

Dai et al. (2017b) build upon work by Dunn et al. (2012b) to estimate the energy intensity of the battery manufacturing, assembly, and cell cycling stages of battery production (Dai et al., 2017b). These data were developed based on battery manufacturing site visits, and from information regarding process details (Wood III et al 2015, Ahmed et al 2016, Ahmed et al 2017). Process energy demand for Li-ion battery production was determined to be an important contributor to total battery production energy due to the need for dry room conditions. Dai et al. combine this energy demand with the energy needed to cycle the battery cells, which they estimate as 1.2kWh/cell, to be 0.161 MMBtu/kWh battery with 82.4% from NG and 17.6% from electricity (2017).

7.3.6. Other Key Materials Production Pathways

Table 42 provides the 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, dolomite, 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, it is then annealed, tempered, and laminated. The major energy inputs for virgin glass production are NG and electricity at the glass plant (gas for melting, annealing, tempering, and laminating; electricity for forming). Dai et al. (2015b) estimated total energy consumed in automotive glass production.

Styrene-butadiene rubber (SBR), made from 75% butadiene and 25% styrene (by weight), is used for the 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 the 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 42. Process assumptions for lead, glass, rubber, and copper

Input or Emission	Unit	Virgin Lead		Recycled Lead Production[a]	Automotive Glass Production[b]	Rubber Production[a]	Copper			
		Ore Mining[a]	Virgin Lead Production[a]				Ore Mining[c]	Smelting/Refining[c]	Chilean Copper Production[d]	Drawing Wire[e]
Fuel										
Residual oil	MMBtu/ton	–	–	–	–	16.76	–	–	8.79	0.84
Diesel	MMBtu/ton	0.49	–	–	–	–	1.03	1.38	1.84	–
Natural gas	MMBtu/ton	–	–	–	12.28	16.76	–	8.61	0.18	–
Coal	MMBtu/ton	–	–	4.14	–	–	–	3.26	–	0.01
Electricity	MMBtu/ton	2.10	–	–	1.97	0.34	1.12	6.53	13.52	1.63
Coke	ton/ton	–	0.61	–	–	–	–	–	8.79	–
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: Dai et al. (2015b)

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

[d] Source: Kelly et al. (2015)

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

Copper is smelted or recovered by leaching it from dilute sulfide ores found in the southwestern U.S. 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 documented in Keoleian et al. (2012), which compiles life cycle inventory data for metals used in PV production (Fthenakis et al. 2009; 2007). Copper is also mined in Chile, which is also included in the GREET database (Kelly et al. 2015).

7.4. Vehicle Assembly, Disposal, and Recycling

Typical vehicle assembly processes include painting; heating, ventilation, and air conditioning (HVAC); material handling; welding; and supplying 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 43.

Table 43. 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	1.47
Non-combustion emissions								
VOC	ton/vehicle	0.002	–	–	–	–	–	–

7.5. References for Section 7

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8. CRADLE-TO-GRAVE GHG RESULTS

8.1. GREENHOUSE GAS EMISSIONS

As in the prior study, C2G GHG emissions (g CO_2e/mi) are calculated for the different vehicle-fuel combinations. The results are given in Table 44 and Table 45 and plotted in Figure 18 and Figure 19. Detailed assumptions underpinning the vehicle-fuel combinations are provided in Sections 2.5–7. We discuss GTL FTD in Section 4.6, CNG in Sections 4.2 and 5.1, biofuels in Sections 4.3 and 5.3–5.4, e-fuels in Sections 4.4 and 5.6, and H_2 pathways in Sections 4.5 and 5.7. The vehicles under investigation are ICEVs, HEVs, PHEVs, H_2 FCEVs, and BEVs. Advanced electricity generation pathways considered for electrification of vehicles include ACC NG generation and CCS, which are discussed in Sections 4.7 and 5.5. Figure 18 and Figure 19 show results for the fuel production pathways and vehicle technologies for midsize sedans and small SUVs, respectively. 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. The FUTURE TECHNOLOGY cases consider the high powertrain technology progression pathway. Figure 18 and Figure 19 can be understood as follows:

- Black line: GHG emissions associated with CURRENT TECHNOLOGY for the associated pathways
- Red line: potential future vehicle efficiency gains. Fuel economy improvement estimates are based on the adoption of advanced vehicle and powertrain technologies in the 2030–2035 timeframe. For electric vehicles, this line corresponds to the default U.S. electricity mix in GREET for the year 2035 in a vehicle with future technology gains.
- Blue line: GHG emissions associated with the production of FUTURE TECHNOLOGY vehicles amortized over the life of the vehicle. This would be the life cycle GHG emissions of the vehicle if it operated on a 0 g CO_2e/mi fuel. Note that vehicle production assumptions here use baseline assumptions from the GREET model for the electricity grid mix, material and vehicle production practices, and carbon capture, and do not consider additional solutions to decarbonize vehicle manufacturing like electrification or use of low-carbon fuels.
- Down-arrows: Potential GHG emissions reductions from low-carbon fuels and electricity in addition to vehicle efficiency gains. The gap between the arrows and lines can be considered as the fuel cycle, or the life cycle emissions associated with operating the vehicle.

For instance, for the gasoline ICEV midsize sedan pathway, the potential vehicle efficiency gains would bring emissions down from 382 g CO_2e/mi to 287 g CO_2e/mi; these emissions could be further reduced to between 79 and 44 g CO_2e/mi by using a low-carbon fuel. We further see that the burden of vehicle production accounts for 33 g CO_2e/mi of the FUTURE TECHNOLOGY emissions. Similarly for the gasoline ICEV small SUV pathway, the potential vehicle efficiency gains would bring emissions down from 429 g CO_2e/mi to 322 g CO_2e/mi; these emissions could be further reduced to between 91 and 52 g CO_2e/mi by using a low-carbon fuel. We further see that the burden of vehicle production accounts for 39 g CO_2e/mi of the FUTURE TECHNOLOGY emissions.

Much like the 2016 C2G study, 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 18 and Figure 19 that large GHG reductions for LDVs are challenging and require consideration of the entire life cycle, including vehicle manufacture, fuel production, and vehicle operation. Achieving a life cycle reduction in GHG emissions is a challenging task and must overcome both technological hurdles as well as cost and market acceptance constraints.

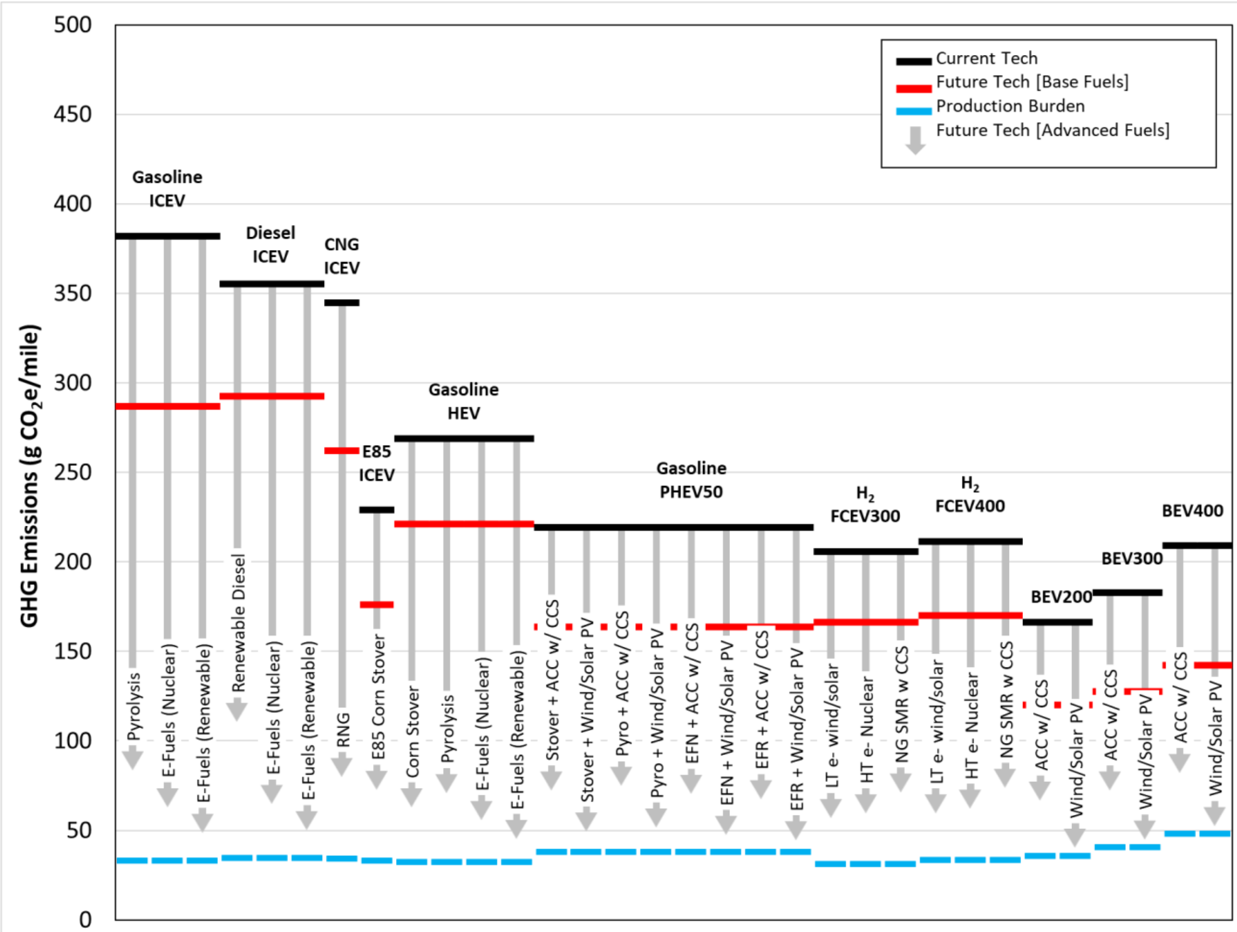

Figure 18. GHG emissions for midsize sedans, assuming high technological progress. Numerical values are given in Table 44.

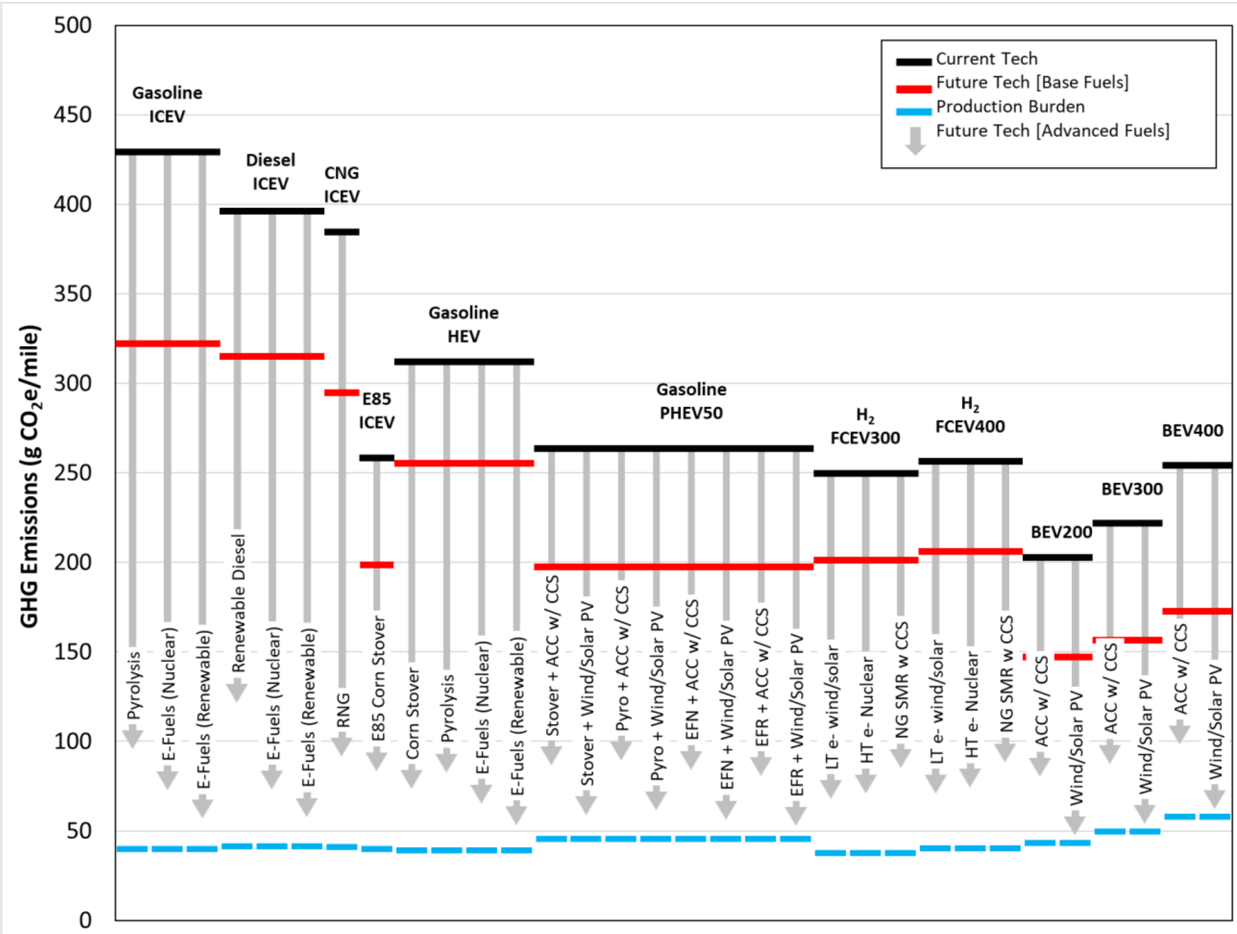

Figure 19. GHG emissions for small SUVs, assuming high technological progress. Numerical values are given in Table 45.

Table 44. GHG emissions for FUTURE TECHNOLOGY case shown in Figure 18 (g CO_2e/mile)

Pathway	Gasoline Turbo ICEV	Diesel ICEV	CNG ICEV	E85 ICEV	Gasoline HEV	Gasoline PHEV50	H_2 FCEV 300	H_2 FCEV 400	BEV200	BEV300	BEV400
CURRENT TECHNOLOGY	382	355	345	229	269	219	206	211	166	182	209
Vehicle efficiency gain	287	293	262	176	221	164	166	170	120	127	142
Forest residue pyrolysis	79	128	–	–	66	–	–	–	–	–	–
Soybean	–	106	–	–	–	–	–	–	–	–	–
E-fuels (nuclear)	58	60	–	–	51	–	–	–	–	–	–
E-fuels (renewable)	44	46	–	–	40	–	–	–	–	–	–
RNG	–	–	75	–	–	–	–	–	–	–	–
Corn stover	–	–	–	68	58	–	–	–	–	–	–
Solar/wind electricity	–	–	–	–	–	–	52	55	36	40	48
Nuclear electrolysis	–	–	–	–	–	–	55	57	–	–	–
NG SMR with CCS	–	–	–	–	–	–	66	69	–	–	–
Stover + ACC w/ CCS	–	–	–	–	–	68	–	–	–	–	–
Stover + wind/solar	–	–	–	–	–	45	–	–	–	–	–
Pyrolysis + ACC w/ CCS	–	–	–	–	–	70	–	–	–	–	–
Pyrolysis + wind/solar	–	–	–	–	–	47	–	–	–	–	–
E-fuel (nuclear) + ACC w/ CCS	–	–	–	–	–	66	–	–	–	–	–
E-fuel (nuclear) + wind/solar	–	–	–	–	–	43	–	–	–	–	–
E-fuel (renewable) + ACC w/ CCS	–	–	–	–	–	63	–	–	–	–	–
E-fuel (renewable) + wind/solar	–	–	–	–	–	40	–	–	–	–	–

Table 45. GHG emissions for the FUTURE TECHNOLOGY case shown in Figure 19 (g CO_2e/mile)

Pathway	Gasoline Turbo ICEV	Diesel ICEV	CNG ICEV	E85 ICEV	Gasoline HEV	Gasoline PHEV50	H_2 FCEV 300	H_2 FCEV 400	BEV200	BEV300	BEV400
CURRENT TECHNOLOGY	429	396	384	258	312	264	250	256	203	221	254
Vehicle efficiency gain	322	315	295	198	255	197	201	206	147	156	173
Forest residue pyrolysis	91	128	–	–	78	–	–	–	–	–	–
Soybean	–	117	–	–	–	–	–	–	–	–	–
E-fuels (Nuclear)	68	68	–	–	60	–	–	–	–	–	–
E-fuels (Renewable)	52	53	–	–	48	–	–	–	–	–	–
RNG	–	–	87	–	–	–	–	–	–	–	–
Corn stover	–	–	–	79	69	–	–	–	–	–	–
Solar/wind electricity	–	–	–	–	–	–	63	66	43	49	57
Nuclear electrolysis	–	–	–	–	–	–	66	69	–	–	–
NG SMR with CCS	–	–	–	–	–	–	80	84	–	–	–
Stover + ACC w/ CCS	–	–	–	–	–	82	–	–	–	–	–
Stover + wind/solar	–	–	–	–	–	54	–	–	–	–	–
Pyrolysis + ACC w/ CCS	–	–	–	–	–	85	–	–	–	–	–
Pyrolysis + wind/solar	–	–	–	–	–	57	–	–	–	–	–
E-fuel (nuclear) + ACC w/ CCS	–	–	–	–	–	79	–	–	–	–	–
E-fuel (nuclear) + wind/solar	–	–	–	–	–	52	–	–	–	–	–
E-fuel (renewable) + ACC w/ CCS	–	–	–	–	–	76	–	–	–	–	–
E-fuel (renewable) + wind/solar	–	–	–	–	–	48	–	–	–	–	–

8.2. TOTAL ENERGY

Figure 20 shows the amount of energy (Btu/mi) by source needed to produce the midsize vehicles and fuels in the study, while 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 20 and Figure 21 are shown in Table 46 and Table 47, respectively.

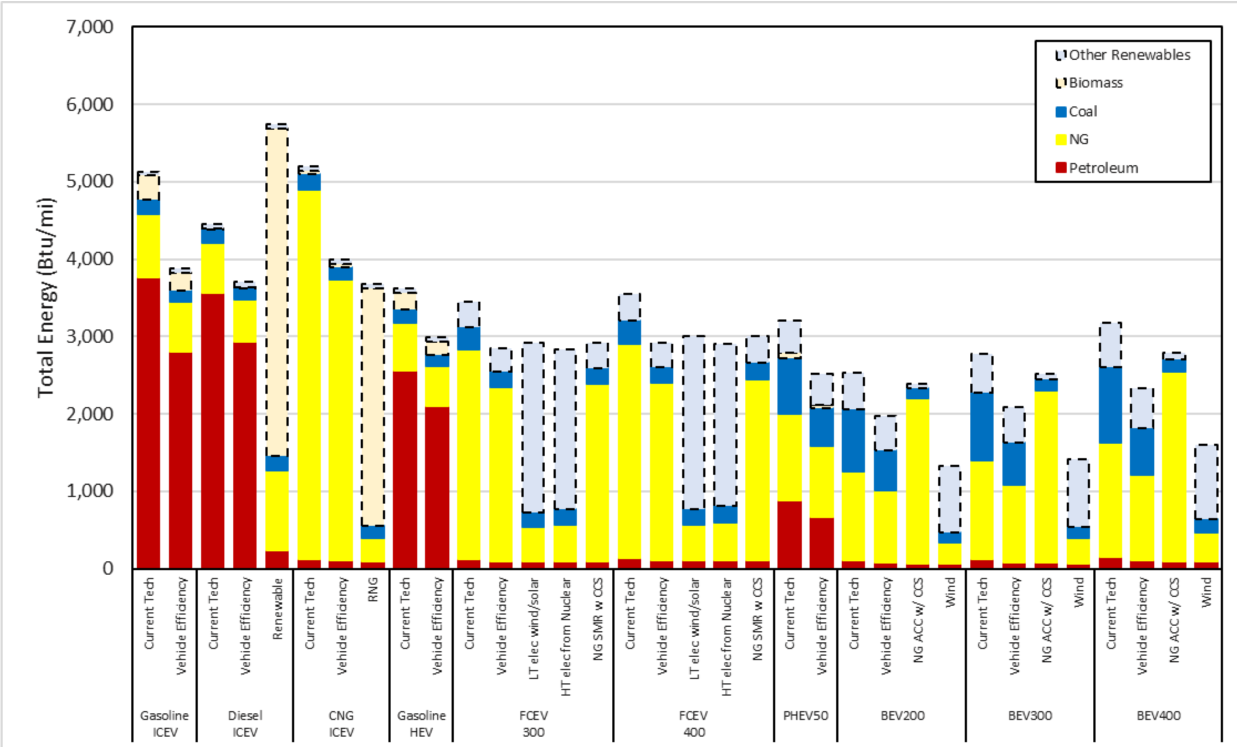

Figure 20. GREET results of energy consumption for all midsize vehicle-fuel combinations (Btu/mi). Each bar is segmented by energy source. Data for this figure are in Table 46.

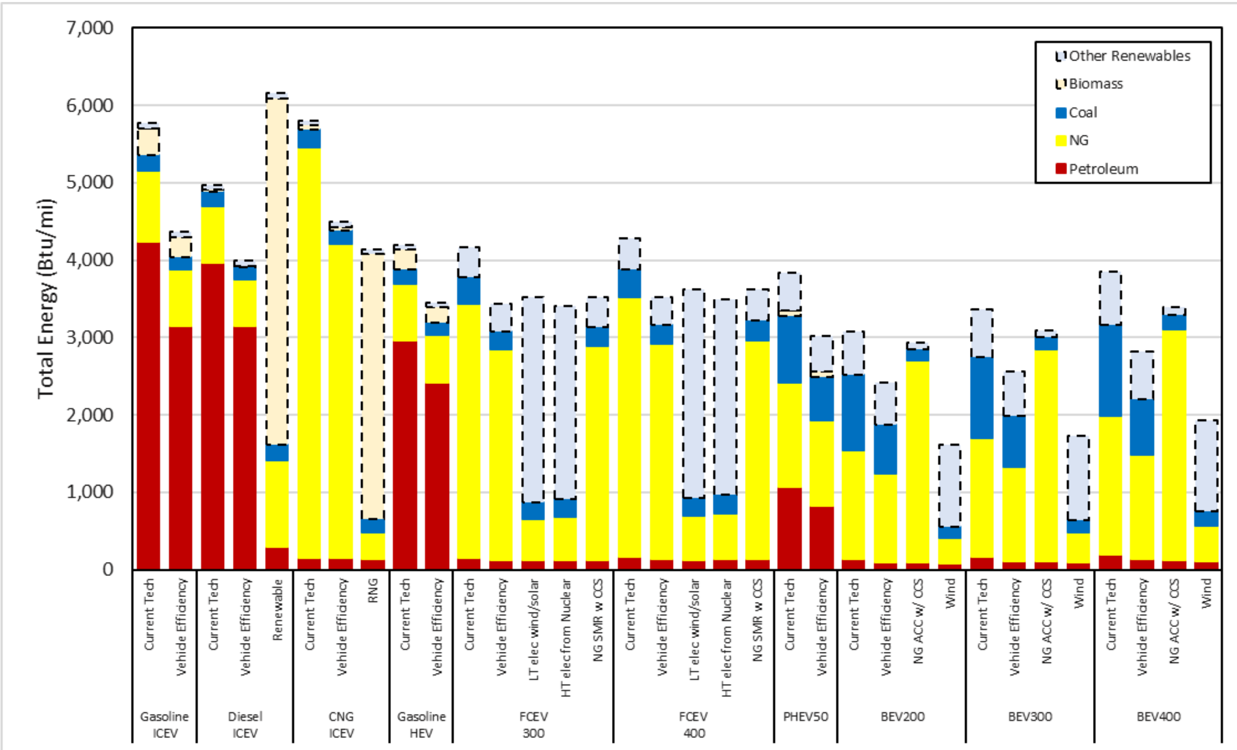

Figure 21. GREET results of energy consumption for all small SUV vehicle-fuel combinations (Btu/mi). Each bar is segmented by energy source. Data for this figure are in Table 47.

Table 46. Total midsize sedan energy consumed, as shown in Figure 20 (Btu/mi)

Vehicle		Total	Petroleum	NG	Coal	Biomass	Other/Renewables
Gasoline ICEV	Current Tech	5,133	3,770	806	186	316	54
	Vehicle Efficiency	3,885	2,808	636	147	236	58
	Pyrolysis	9,283	(112)	1,516	(187)	8,066	-
	E-fuels (Nuclear)	5,001	15	43	18	-	4,925
	E-Fuels (Renewable)	6,693	7	4	2	-	6,680
Diesel ICEV	Current Tech	4,456	3,564	642	172	20	58
	Vehicle Efficiency	3,706	2,936	548	141	18	62
	Renewable	5,747	245	1,030	188	4,223	62
	E-fuels (Nuclear)	4,957	15	43	18	-	4,882
	E-Fuels (Renewable)	6,634	7	4	2	-	6,621
CNG ICEV	Current Tech	5,203	118	4,775	209	44	58
	Vehicle Efficiency	3,997	108	3,631	159	38	61
	RNG	3,684	96	298	156	3,073	61
E85	Current Tech	6,865	234	447	96	6,089	-
	Vehicle Efficiency	5,103	174	332	71	4,526	-
	Corn Stover	8,395	264	192	(78)	8,017	-
Gasoline HEV	Current Tech	3,616	2,555	620	175	212	53
	Vehicle Efficiency	2,990	2,096	525	140	175	54
FCEV 300	Current Tech	3,446	120	2,708	286	-	331
	Vehicle Efficiency	2,852	100	2,252	190	-	310
	LT Elec Wind/Solar	2,926	93	448	189	-	2,196
	HT Elec. Nuclear	2,827	97	470	198	-	2,063
	NG SMR w/ CCS	2,924	100	2,285	210	-	329
FCEV 400	Current Tech	3,545	133	2,771	299	-	341
	Vehicle Efficiency	2,927	110	2,300	198	-	318
	LT Elec. Wind/Solar	3,002	104	472	197	-	2,230
	HT Elec. Nuclear	2,902	108	495	205	-	2,094
	NG SMR w/ CCS	3,001	111	2,334	218	-	338
PHEV50	Current Tech	3,200	879	1,122	724	64	410
	Vehicle Efficiency	2,518	671	918	483	49	397
BEV200	Current Tech	2,531	106	1,155	802	-	468
	Vehicle Efficiency	1,976	76	934	521	-	445
	NG ACC w/ CCS	2,395	69	2,135	127	-	65
	Wind	1,325	63	280	125	-	857
BEV300	Current Tech	2,777	128	1,278	865	-	506
	Vehicle Efficiency	2,091	87	994	545	-	464
	NG ACC w/ CCS	2,522	80	2,228	140	-	74
	Wind	1,421	73	321	138	-	888
BEV400	Current Tech	3,179	157	1,473	976	-	573
	Vehicle Efficiency	2,330	105	1,115	600	-	511
	NG ACC w/ CCS	2,797	97	2,453	160	-	87
	Wind	1,604	89	385	159	-	971

Table 47. Total small SUV energy consumed, as shown in Figure 20 (Btu/mi)

Vehicle		Total	Petroleum	NG	Coal	Biomass	Other Renewables
Gasoline ICEV	Current Tech	5,767	4,234	915	206	353	59
	Vehicle Efficiency	4,362	3,150	723	162	263	63
	Pyrolysis	10,304	(124)	1,683	(208)	8,954	-
	E-fuels (Nuclear)	5,538	16	48	20	-	5,454
	E-Fuels (Renewable)	7,411	7	5	2	-	7,397
Diesel ICEV	Current Tech	4,969	3,968	727	189	22	62
	Vehicle Efficiency	3,995	3,144	610	155	19	67
	Renewable	6,160	290	1,121	204	4,478	67
	E-fuels (Nuclear)	5,271	16	46	19	-	5,192
	E-Fuels (Renewable)	7,055	7	5	2	-	7,041
CNG ICEV	Current Tech	5,800	157	5,302	230	48	63
	Vehicle Efficiency	4,492	146	4,063	175	42	66
	RNG	4,143	132	348	172	3,425	66
E85	Current Tech	7,620	259	496	106	6,759	-
	Vehicle Efficiency	5,651	192	368	79	5,012	-
	Corn Stover	9,296	292	213	(86)	8,877	-
Gasoline HEV	Current Tech	4,190	2,970	721	197	245	58
	Vehicle Efficiency	3,449	2,422	609	157	201	59
FCEV 300	Current Tech	4,161	150	3,286	339	-	385
	Vehicle Efficiency	3,436	126	2,726	224	-	360
	LT Elec. Wind/Solar	3,526	118	534	223	-	2,651
	HT Elec. Nuclear	3,407	123	562	233	-	2,489
	NG SMR w/ CCS	3,525	127	2,766	248	-	384
FCEV 400	Current Tech	4,278	166	3,361	354	-	396
	Vehicle Efficiency	3,528	139	2,786	234	-	371
	LT Elec. Wind/Wolar	3,620	131	564	232	-	2,693
	HT Elec. Nuclear	3,499	136	592	243	-	2,529
	NG SMR w/ CCS	3,618	140	2,826	258	-	394
PHEV50	Current Tech	3,841	1,072	1,344	860	77	488
	Vehicle Efficiency	3,026	824	1,100	572	59	471
BEV200	Current Tech	3,084	136	1,407	973	-	569
	Vehicle Efficiency	2,412	100	1,140	631	-	541
	NG ACC w/ CCS	2,928	91	2,619	145	-	73
	Wind	1,609	83	334	144	-	1,049
BEV300	Current Tech	3,365	161	1,548	1,045	-	612
	Vehicle Efficiency	2,561	114	1,218	662	-	566
	NG ACC w/ CCS	3,092	105	2,740	163	-	85
	Wind	1,735	96	388	161	-	1,089
BEV400	Current Tech	3,858	198	1,788	1,180	-	693
	Vehicle Efficiency	2,821	133	1,350	722	-	617
	NG ACC w/ CCS	3,391	124	2,983	185	-	100
	Wind	1,935	114	459	183	-	1,178

9. LEVELIZED COST OF DRIVING ANALYSIS

The fuel cost data from Section 5 and the vehicle cost and fuel economy data from Section 6 are 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 the present study LCD is defined as the sum of the amortized vehicle cost per mile (LCD_{veh}) and the fuel cost per mile (LCD_{fuel}): $LCD = LCD_{veh} + LCD_{fuel}$. The LCD has units of dollars per mile driven. The LCD calculation only considers vehicle (including the EVSE for the BEVs and PHEVs) and fuel costs. Other costs such as insurance, maintenance, and parking are not considered here. 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 vehicle miles travelled (VMT). Costs are considered in real dollars (2020$), 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 2020$/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:

$$Vehicle\ Cost\ (net) = \sum_{i=1}^{t} \frac{LCD_{veh} * VMT_i}{(1+D)^i} \tag{2}$$

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:

$$LCD_{fuel} = \frac{Fuel\ Cost}{FuelEconomy} \tag{3}$$

Where fuel cost is in units of $/gge and fuel economy is in units of mi/gge. As noted, the LCD metric depends on an assumption of annual VMT. The VMT assumption in this calculation is based on the National Highway Traffic Safety Administration (NHTSA) 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 the vehicle 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, which is the assumed vehicle EOL in our analysis. The total number of miles traveled over the vehicle lifetime is 178,102. We assume that BEVs have sufficient driving capacity to function as equivalent replacements of ICEVs on a VMT basis.

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).

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 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 of approximately 15–20% over the first 3–9 years. 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 assume the same depreciation rate for all vehicle technologies. Appendix E illustrates how the LCD calculations are performed.

Note that the cost analysis here does not provide a quantitative estimate of potential maintenance cost savings. However, other studies suggest that light-duty BEVs reduce maintenance costs compared to ICEVs by approximately 40% (Burnham, et al. 2021).

9.2. LCD RESULTS

Using the analysis framework described above, LCD estimates are developed for all vehicle-fuel pathways for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases. All costs are presented in 2020$. 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 is developed for the CURRENT TECHNOLOGY (MY2020) and FUTURE TECHNOLOGY cases (MY2030–2035) 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 Figure 22, Figure 23, Figure 24, and Figure 25.

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 case, the more commercially established vehicles (gasoline, diesel, E85, and HEV) have LCDs below $0.45/mi for midsize sedans, and below $0.50/mi for small SUVs. Emerging vehicle technologies, such as BEVs, longer-range PHEVs, and FCEVs for midsize sedans, have LCDs exceeding $0.50/mi, except for BEV200 ($0.45/mi). The same trend holds for small SUVs, with PHEV, BEV, and FCEV costs exceeding $0.55/mi. As shown in the FUTURE TECHNOLOGY case, improvements in technology and cost suggest that most vehicles will be below $0.50/mi in the baseline conditions for both midsize sedans and small SUVs, with BEVs having the largest cost reductions.

The C2G study uses a range of estimates for vehicle and fuel costs for the CURRENT TECHNOLOGY case. The resulting LCD results based on these high and low fuel and vehicle cost ranges are shown as uncertainty bars in Figure 22 and Figure 23. Additionally, as described in Section 5.7, a CURRENT TECHNOLOGY low-volume hydrogen fuel cost estimate is developed for hydrogen fuel to better understand the impact of hydrogen fuel cost in the near term, shown as a black arrow. For FCEVs in the CURRENT TECHNOLOGY case, the low-volume cost of hydrogen increases the midsize sedan FCEV LCD from $0.70/mi to $0.78/mi, depending on the range, and the small SUV FCEV LCD from $0.830/mi to $0.93/mi.

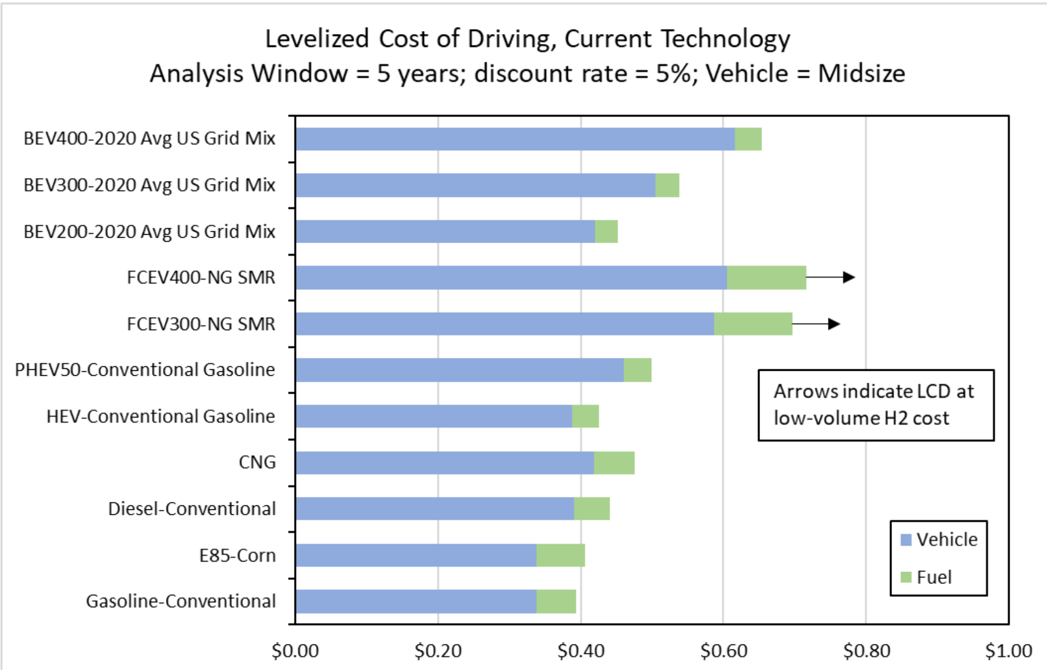

Figure 22. LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY midsize sedan case

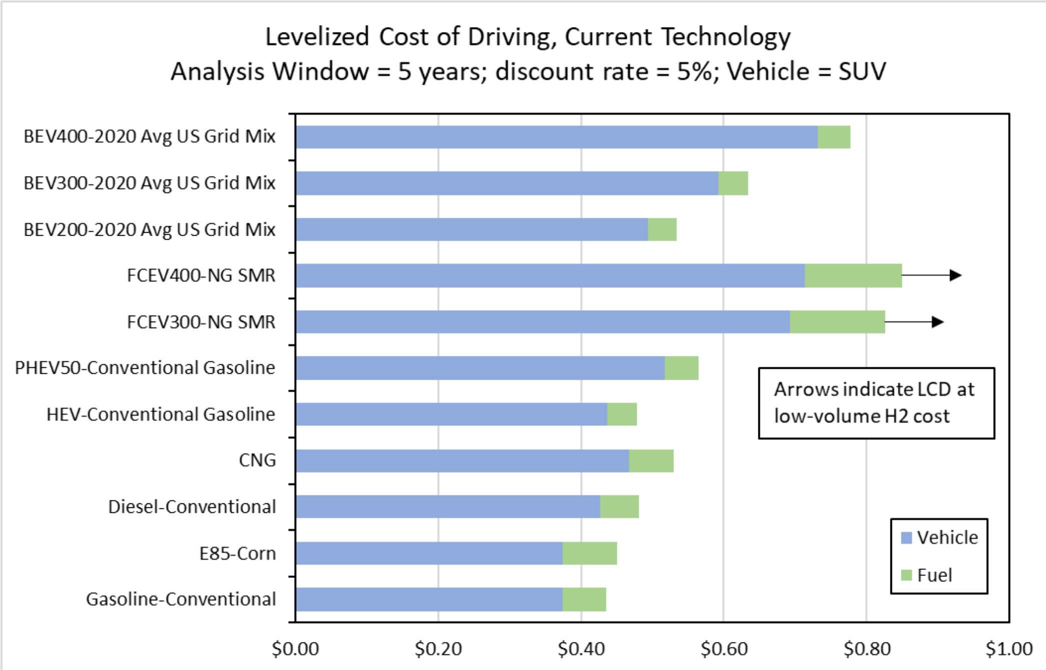

Figure 23. LCD by vehicle-fuel pathway for the CURRENT TECHNOLOGY small SUV case

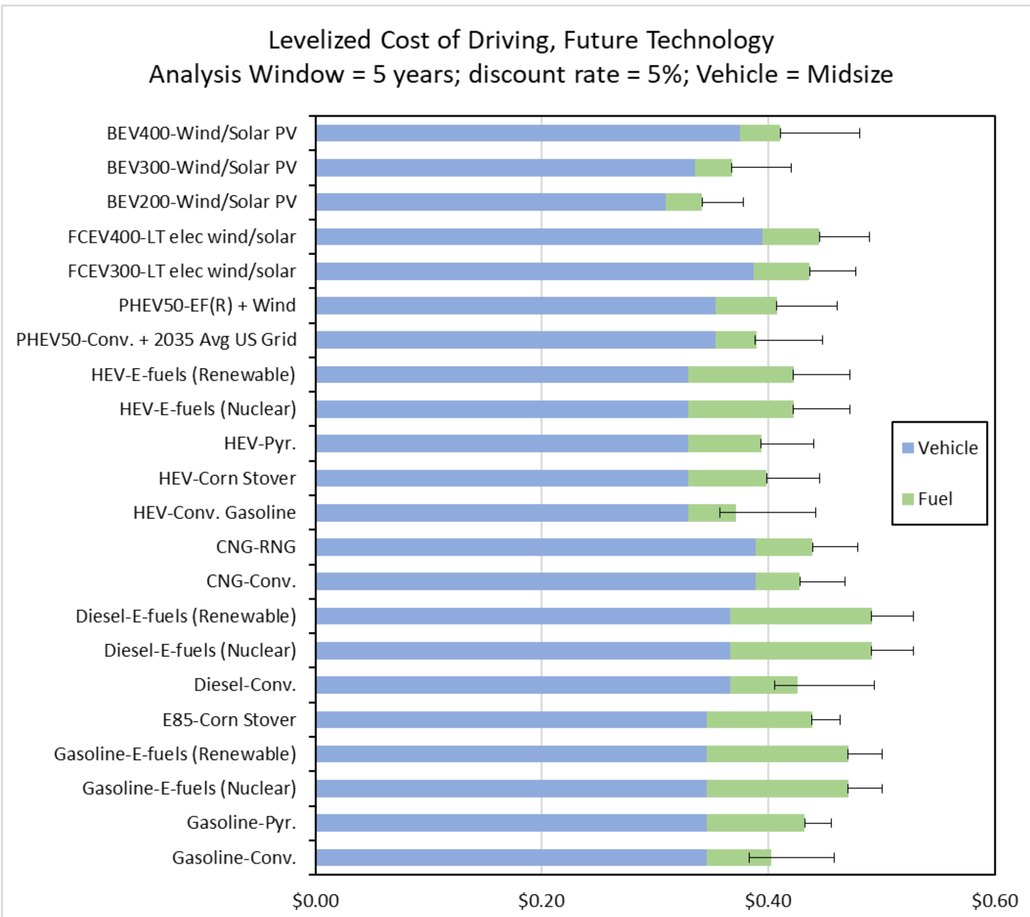

Figure 24. LCD by vehicle-fuel pathway for FUTURE TECHNOLOGY midsize sedan case

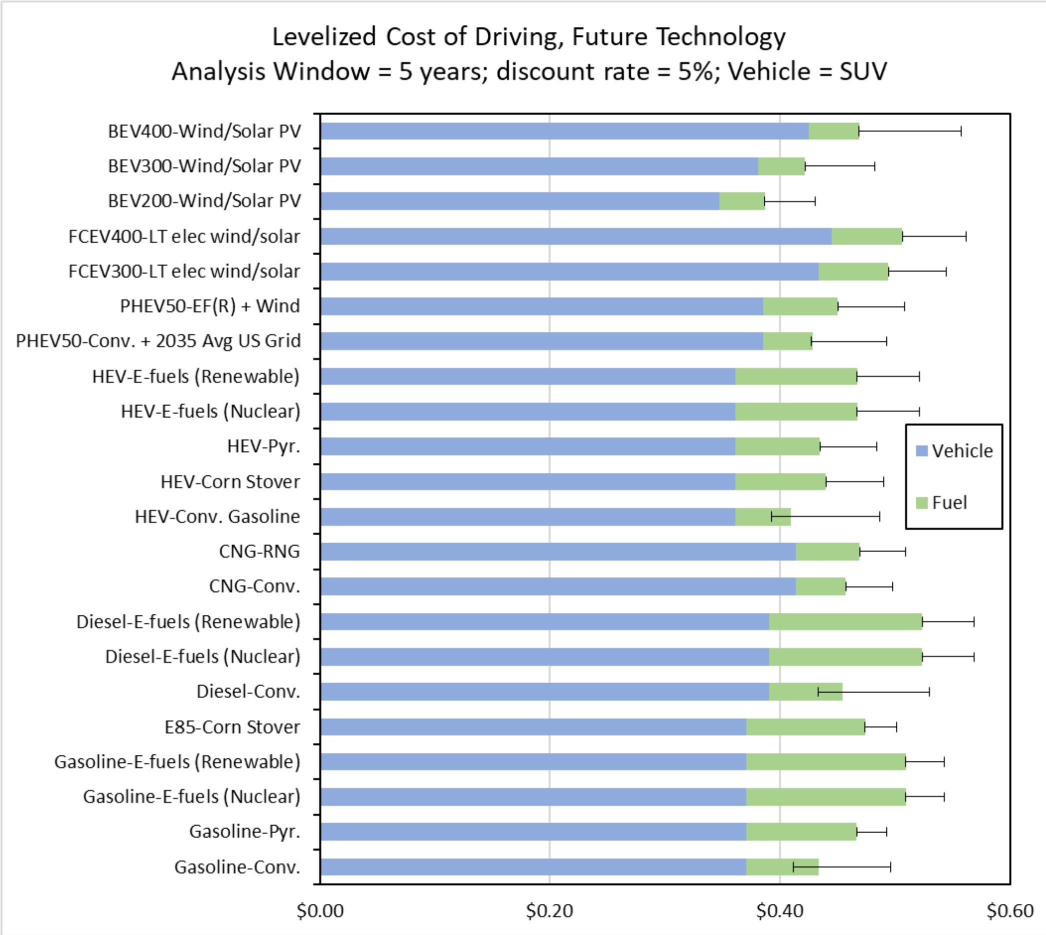

Figure 25. LCD by vehicle-fuel pathway for FUTURE TECHNOLOGY small SUV case

As described in Sections 5 and 6, vehicle and fuel cost ranges are developed for the FUTURE TECHNOLOGY case. The uncertainty bars in Figure 24 (midsize sedans) and Figure 25 (small SUVs) show the range of LCD results for each vehicle-fuel pathway (evaluated over a 5-year ownership period using a 5% discount rate) if low and high estimates are used for the vehicle and fuel costs.

9.3. LCD SENSITIVITY RESULTS

In addition to the illustrative base case, sensitivity analyses of the LCD for the various vehicle-fuel pathways are conducted for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases. As with the baseline LCD analysis, the 3-year and 15-year LCD analysis uses 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 are shown in Figure 26 and Figure 27 for the midsize sedan and small SUV, respectively. The FUTURE TECHNOLOGY cases are shown in Figure 28 and Figure 29 for the midsize sedan and small SUV, respectively.

To better understand the full range of potential LCD results, sensitivity analyses are conducted to develop upper- and lower-bound LCD estimates for each vehicle-fuel pathway for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases. The upper-bound LCD estimates for the CURRENT TECHNOLOGY case are based on a 3-year ownership period using a 7% discount rate. The lower-bound

LCD estimates are 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 are used. The results for the CURRENT TECHNOLOGY case are shown in Figure 30 and Figure 31 for the midsize sedan and small SUV, respectively.

Upper- and lower-bound LCD estimates are made for the FUTURE TECHNOLOGY case. As with the CURRENT TECHNOLOGY case, the upper-bound LCD estimate for the FUTURE TECHNOLOGY case assumes a 3-year ownership period using a 7% discount rate. The upper- and lower-bound LCD estimates for each vehicle-fuel pathway for the FUTURE TECHNOLOGY case (along with the base case results) are shown in Figure 32 and Figure 33 for the midsize sedan and small SUV, respectively.

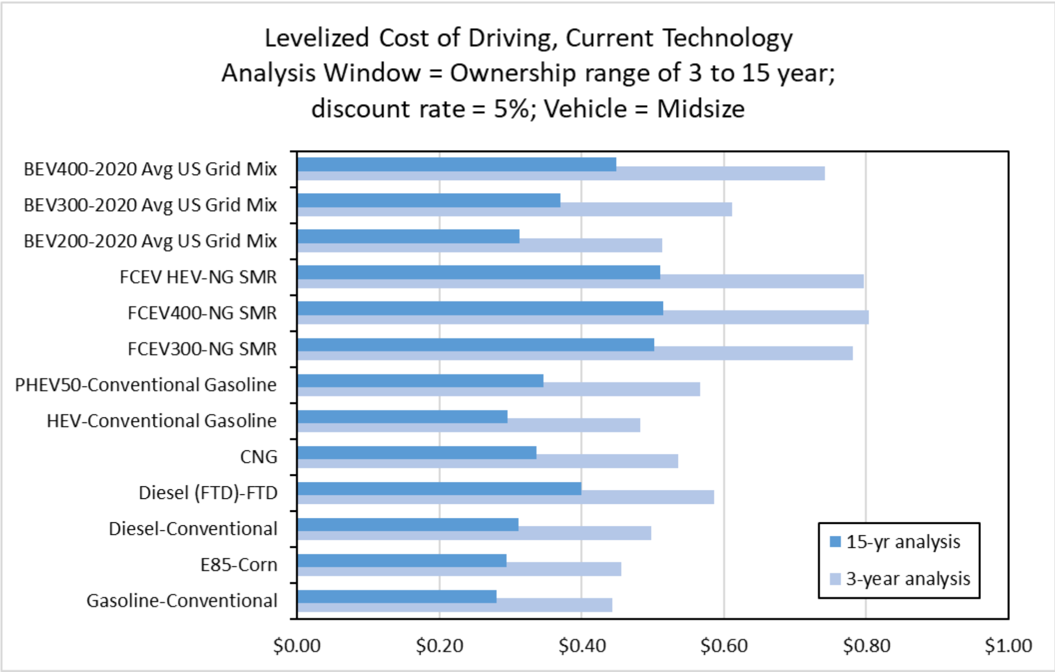

Figure 26. 3-year and 15-year LCD results by vehicle-fuel pathway for the CURRENT TECHNOLOGY midsize sedan case

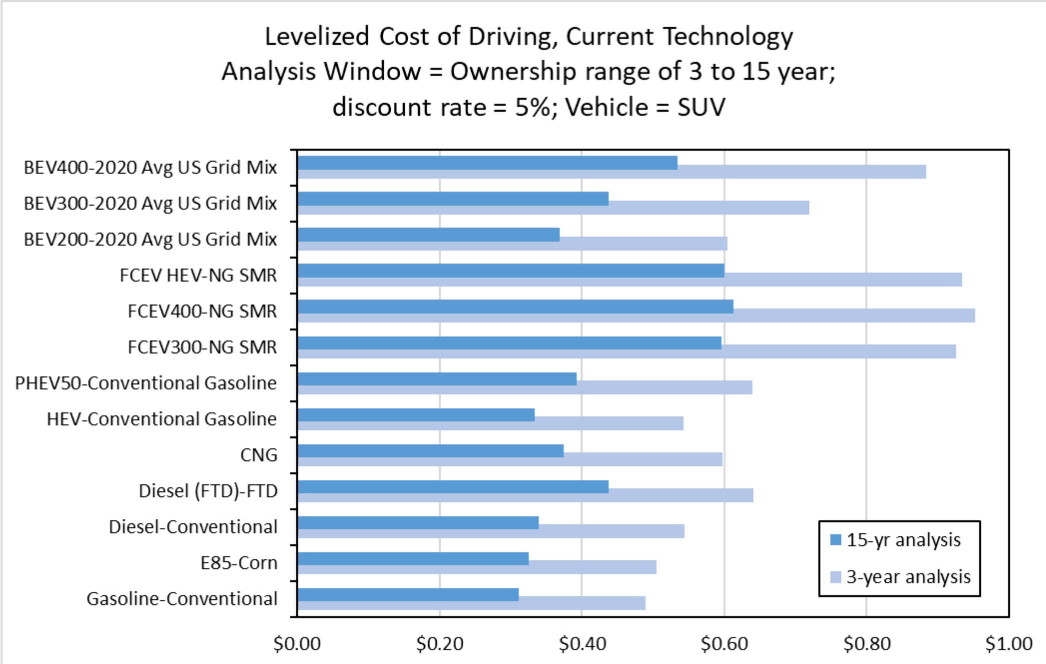

Figure 27. 3-year and 15-year LCD results by vehicle-fuel pathway for the CURRENT TECHNOLOGY small SUV case

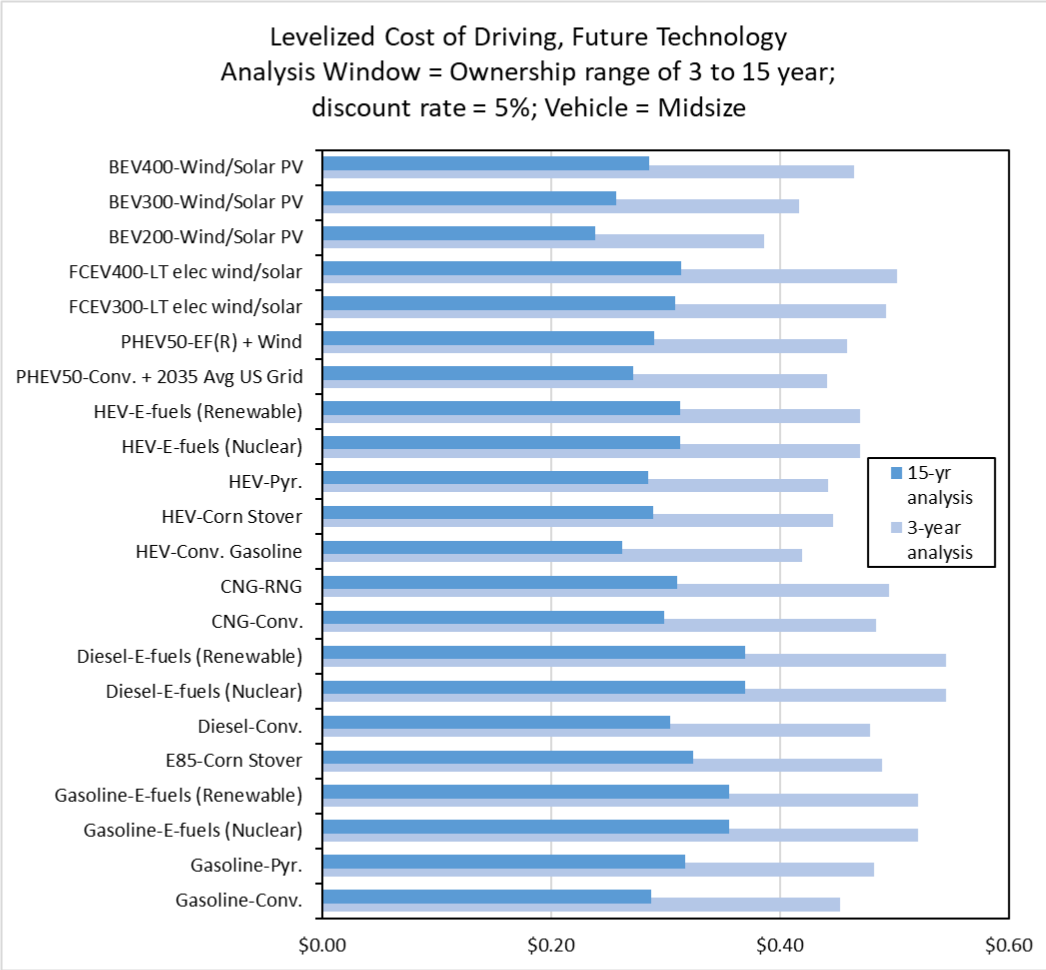

Figure 28. 3-year and 15-year LCD results by vehicle-fuel pathway for the FUTURE TECHNOLOGY midsize sedan case

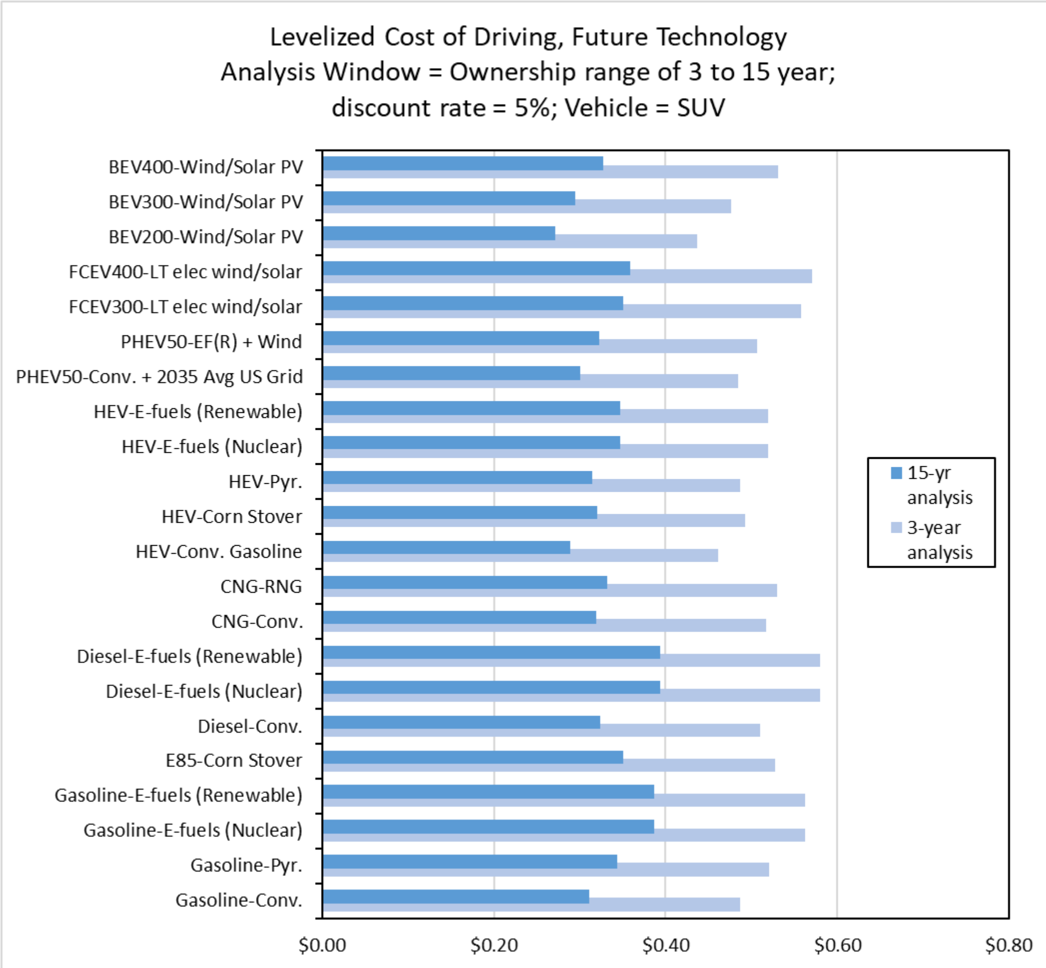

Figure 29. 3-year and 15-year LCD results by vehicle-fuel pathway for FUTURE TECHNOLOGY small SUV case

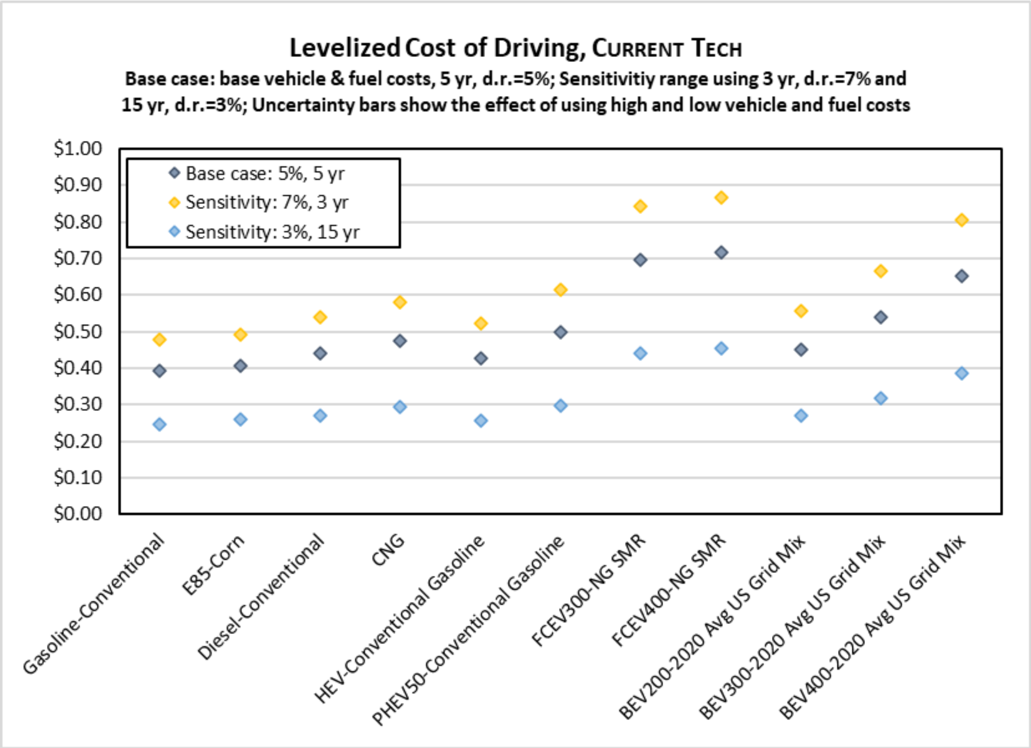

Figure 30. Upper- and lower-bound LCD results by vehicle-fuel pathway for the Current Technology midsize sedan case

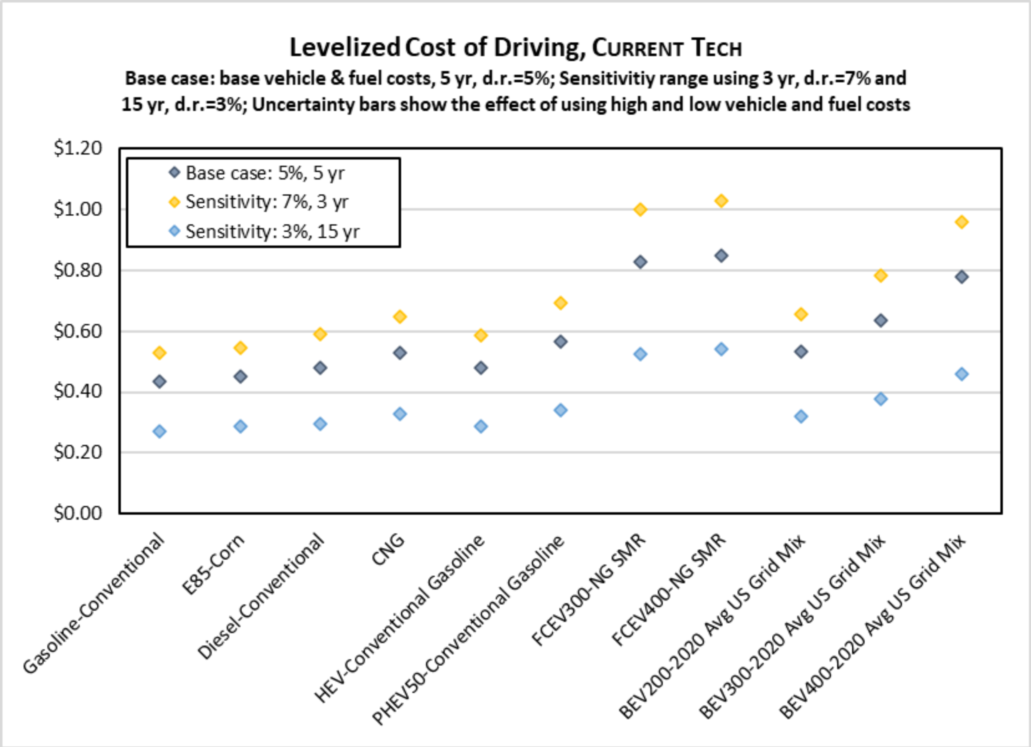

Figure 31. Upper- and lower-bound LCD results by vehicle-fuel pathway for the Current Technology small SUV case

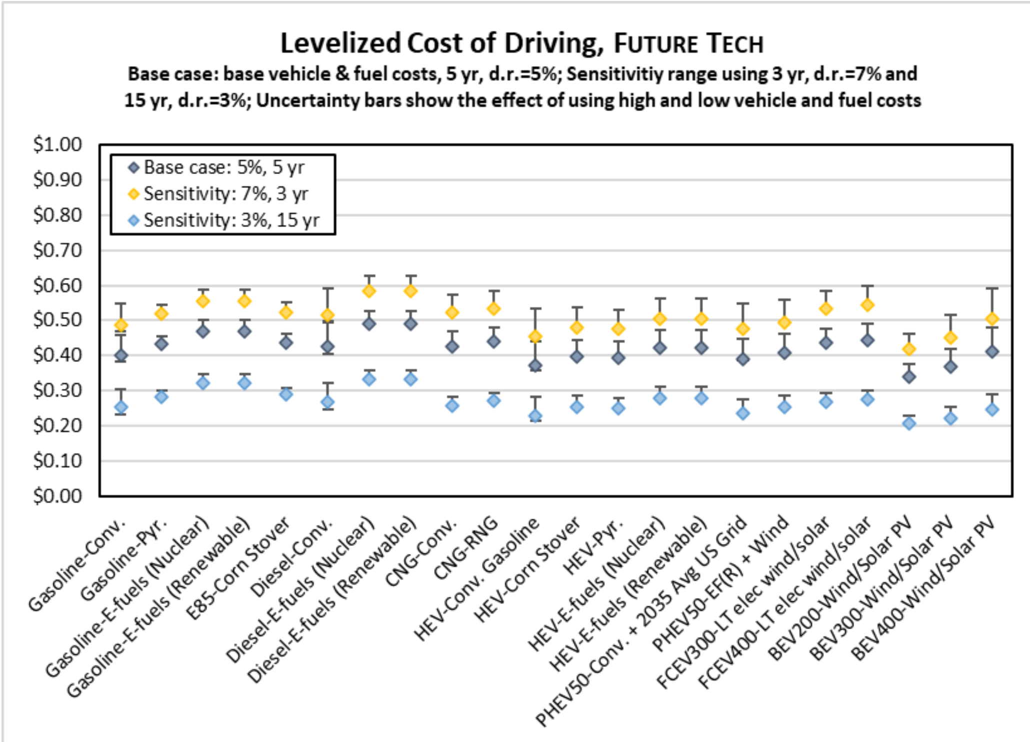

Figure 32. Upper- and lower-bound LCD results by vehicle-fuel pathway for the FUTURE TECHNOLOGY midsize sedan case

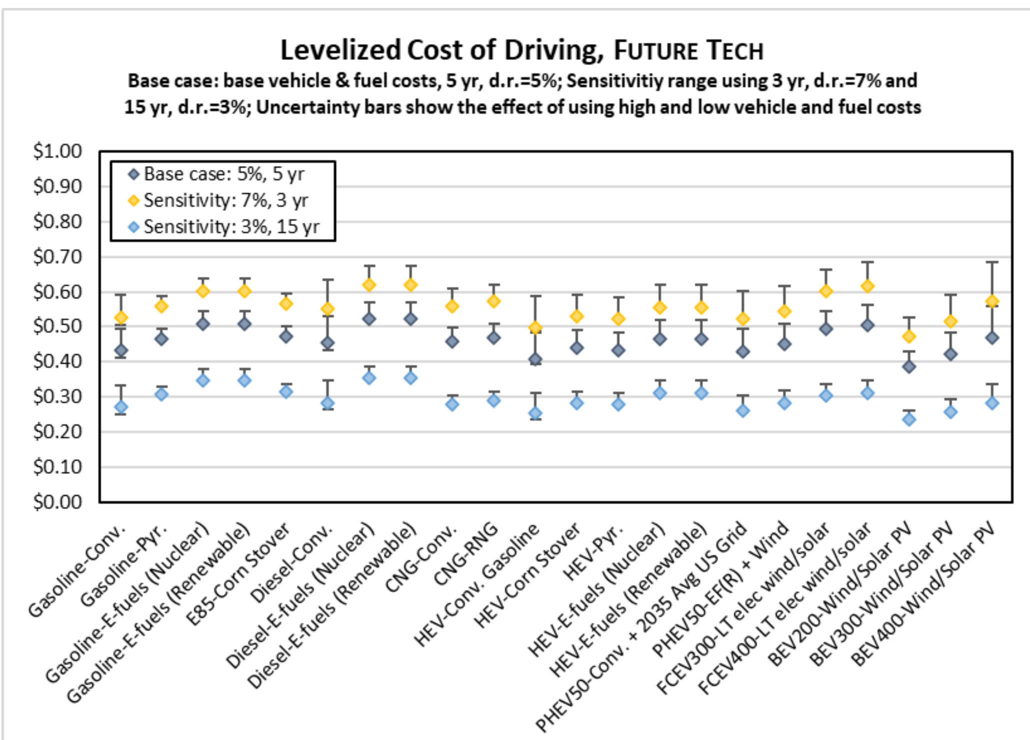

Figure 33. Upper- and lower-bound LCD results by vehicle-fuel pathway for the Future Technology small SUV case

9.4. REFERENCES FOR SECTION 9

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

10. COST OF AVOIDED GHG EMISSIONS

To allow for 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. Finally, while negative abatement costs can be computed, they are not useful because it is unclear whether the negative quantity is in the numerator (i.e., the alternative technology has higher emissions and hence negative abatement) or in the denominator (i.e., the alternative technology has lower cost and hence negative additional cost).

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 life cycle GHG emissions assessment (Section 8) and 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 34). The analysis is conducted for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, with the alternative vehicle platform compared to the equivalent CURRENT TECHNOLOGY (2020) and FUTURE TECHNOLOGY (2030–2035) ICEVs, respectively. The calculation is conducted considering full lifetime (15-year) costs and emissions.[11] 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 is 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.

[11] As an example, in the CURRENT TECHNOLOGY case (Table 48), the gasoline HEV pathway has a 15-year LCD of \$0.296/mi, compared to the 15-year LCD of \$0.281/mi for gasoline ICEVs (values are rounded, as shown in (Table 48). GHG emissions of HEVs are 270 g CO_2e/mi, compared to 383 g CO_2e/mi for ICEVs. The cost of avoided carbon for the HEV pathway is (\$0.30-\$0.28) ÷ ((383 – 270)/1,000,000). When solved using actual (non-rounded) values, this equates to a cost of avoided carbon of \$135.80/tonne. This is reported in a rounded format as \$140/tonne in Table 52.

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

Figure 34. 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 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 LDV market or vehicle usage.

The alternative vehicle-fuel platforms in the FUTURE TECHNOLOGY case are compared to an improved (MY2030–2035) gasoline ICEV, therefore the cost of avoided GHG emissions metric only considers the cost of GHG reductions specifically associated with the alternative vehicle-fuel technologies. We do not address the cost of avoided GHG emissions for improvements to the vehicle glider (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 case considers the cost of avoided GHG emissions based on MY2020 vehicle technologies with vehicle costs modeled at high-volume production at a level which captures the economies of scale. Fuel costs are also modeled for 2020, 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 2020$. Key data for the cost of avoided GHG emissions are shown in Table 48 and Table 49 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 vehicle cost (less its residual value in the 3-year case) and fuel cost, but it does not include other costs of driving, such as maintenance, repairs, insurance, registration, taxes, etc. Sufficient data to differentiate these costs across vehicle-fuel platforms were not available. In the absence of data to the contrary, we assume that costs associated with maintenance, repairs, insurance, registration, and taxes are equal across platforms, and hence do not factor into the estimation of CO_2 abatement cost.

Table 48. Costs and GHG emissions for the CURRENT TECHNOLOGY midsize sedan case

Base Case (5% discount rate, mid-point fuel cost)		**Vehicle Cost**	**Fuel Cost**	**Vehicle F/E**	**GHG Emissions**	**3-year Cost**	**15-year Cost**
Fuel	**Pathway**	**(2020$)**	**($/gge)**	**(mpgge)**	**(g CO_2e/mi)**	**($/mi)**	**($/mi)**
Gasoline	Conventional	28,630	1.69	30.7	383	0.44	0.28
E85	Corn	28,630	2.08	30.7	272	0.46	0.29
Diesel	Conventional	33,092	1.67	33.9	356	0.50	0.31
CNG	CNG	35,420	1.57	27.7	346	0.54	0.34
HEV	Conventional Gasoline	32,860	1.69	45.7	270	0.48	0.30
PHEV50	Conventional Gasoline	38,932	1.69/4.01	45.6/101.4	221	0.57	0.35
FCEV300	NG SMR	49,591	7.30	66.5	207	0.78	0.50
FCEV400	NG SMR	51,085	7.30	65.5	213	0.80	0.51
BEV200	2020 Avg U.S. Grid Mix	35,485	4.01	124.3	168	0.51	0.31
BEV300	2020 Avg U.S. Grid Mix	42,660	4.01	118.3	184	0.61	0.37
BEV400	2020 Avg U.S. Grid Mix	52,068	4.01	107.1	211	0.74	0.45

Table 49. Costs and GHG emissions for the CURRENT TECHNOLOGY small SUV case

Base Case (5% discount rate, mid-point fuel cost)		**Vehicle Cost**	**Fuel Cost**	**Vehicle F/E**	**GHG Emissions**	**3-year Cost**	**15-year Cost**
Fuel	**Pathway**	**(2020$)**	**($/gge)**	**(mpgge)**	**(g CO_2e/mi)**	**($/mi)**	**($/mi)**
Gasoline	Conventional	31,664	1.69	27.5	431	0.49	0.31
E85	Corn	31,664	2.08	27.5	306	0.50	0.33
Diesel	Conventional	36,124	1.67	30.6	397	0.54	0.34
CNG	CNG	39,466	1.57	25.1	386	0.60	0.37
HEV	Conventional Gasoline	36,890	1.69	39.6	313	0.54	0.33
PHEV50	Conventional Gasoline	43,791	1.69/4.01	37.9/84.2	265	0.64	0.39
FCEV300	NG SMR	58,517	7.30	54.6	251	0.93	0.60
FCEV400	NG SMR	60,358	7.30	53.8	258	0.95	0.61
BEV200	2020 Avg U.S. Grid Mix	41,756	4.01	101.1	204	0.61	0.37
BEV300	2020 Avg U.S. Grid Mix	50,065	4.01	96.6	223	0.72	0.44
BEV400	2020 Avg U.S. Grid Mix	61,881	4.01	87.7	256	0.88	0.53

Lifetime costs (vehicle and fuel) versus GHG emissions for the CURRENT TECHNOLOGY case of midsize sedans are shown in Figure 35 (lifetime) and Figure 36 (first owner perspective), and those for small SUVs are shown in Figure 37 (lifetime) and Figure 38 (first owner perspective). These figures present emissions over the noted time frame on the primary x-axis, and the percent reduction in emissions compared to the conventional gasoline vehicle on the secondary x-axis. The lifetime vehicle cost is shown on the y-axis. The results indicate opportunities to reduce GHG emissions with all powertrains (all data points lie to the left of the filled black square gasoline conventional vehicle). However, cost reductions are not observed for the CURRENT TECHNOLOGY cases (all data points lie above the filled black square gasoline conventional vehicle).

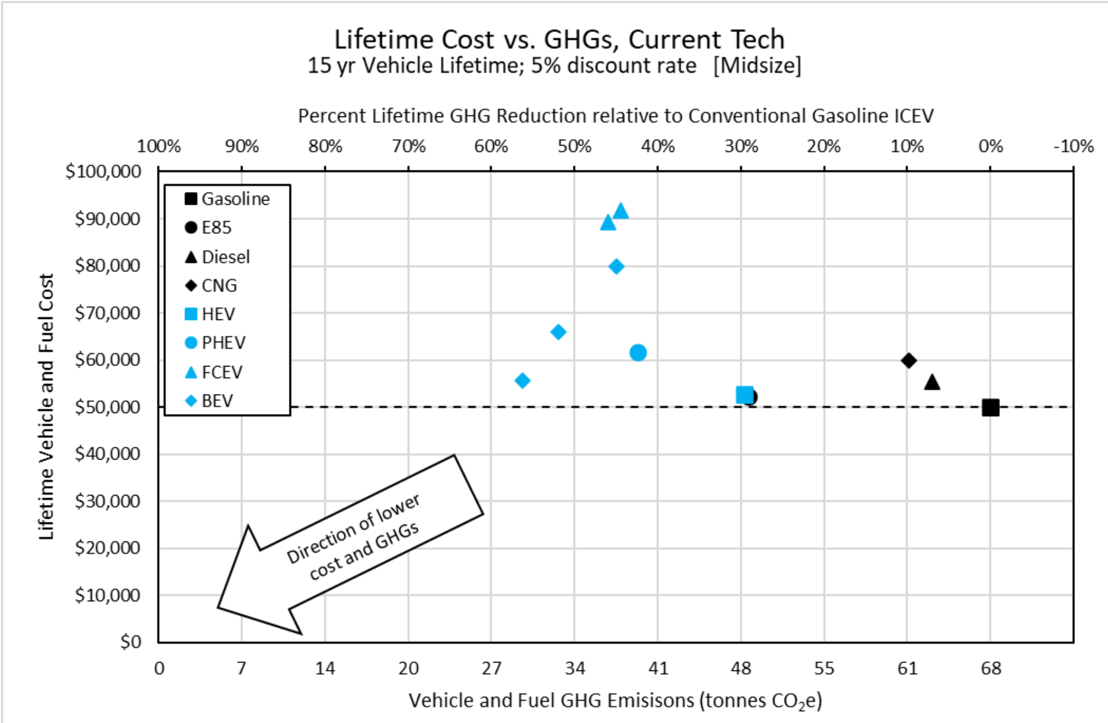

Figure 35. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY midsize sedan case for the CURRENT TECHNOLOGY case over its lifetime

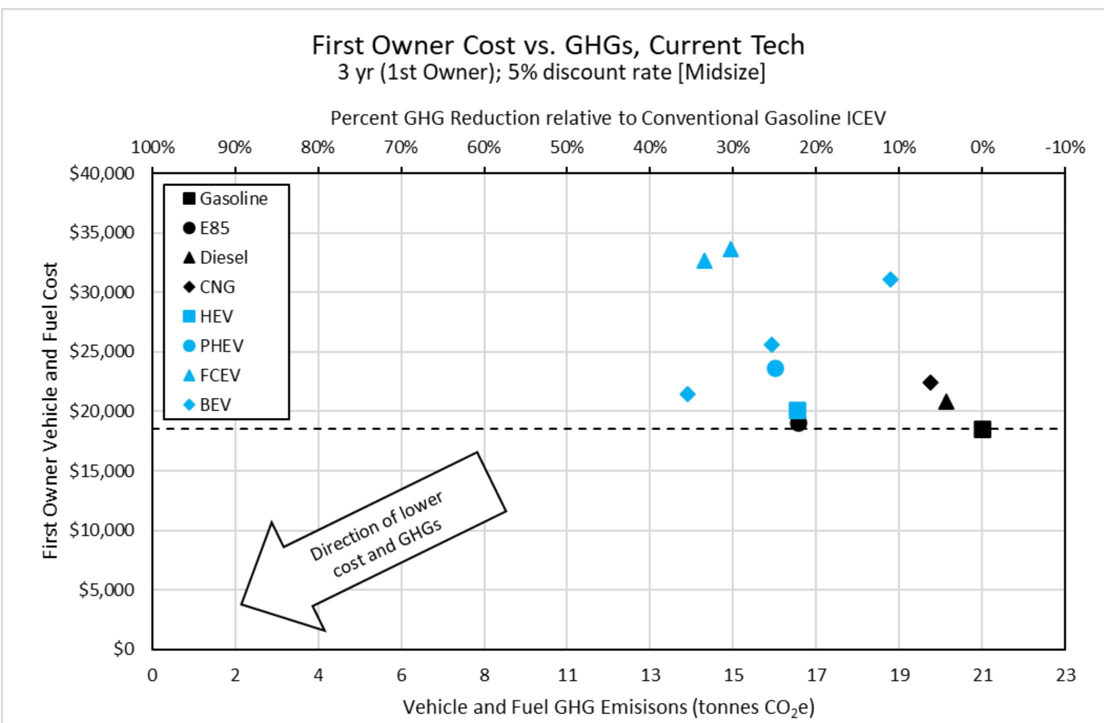

Figure 36. First owner costs versus GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY midsize sedan case for the CURRENT TECHNOLOGY case during the first owner

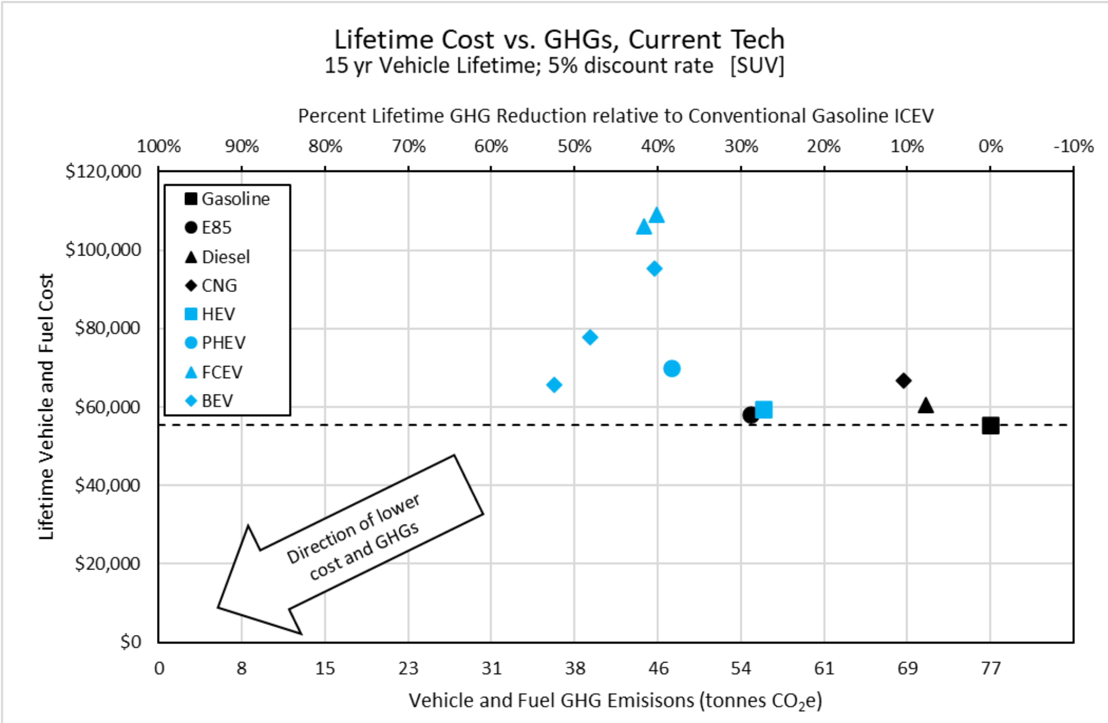

Figure 37. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY small SUV case for the CURRENT TECHNOLOGY case over its lifetime

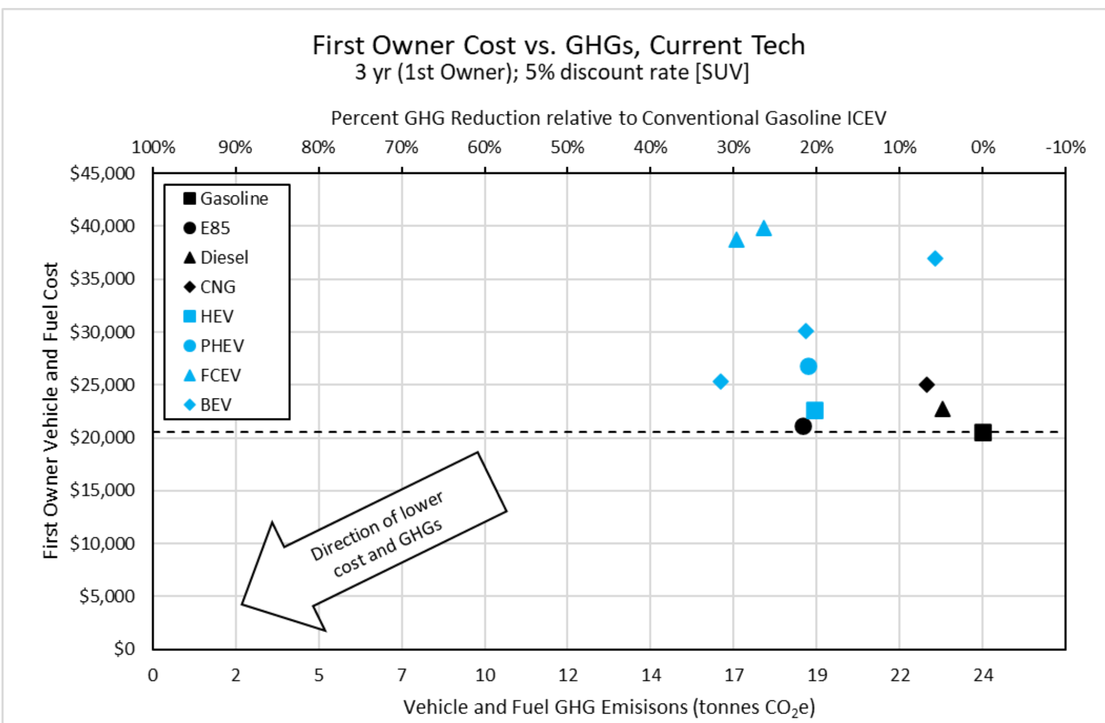

Figure 38. First owner costs versus GHG emissions by vehicle-fuel pathway for the CURRENT TECHNOLOGY small SUV case for the CURRENT TECHNOLOGY case during the first owner

10.3. COST OF AVOIDED GHG EMISSIONS: FUTURE TECHNOLOGY CASE

The FUTURE TECHNOLOGY case considers the modeled cost of avoided GHG emissions based on MY2030–2035 vehicle technologies. As with the CURRENT TECHNOLOGY case, vehicle costs are modeled at high-volume production. Fuel costs are also modeled for 2030–2035, with fuels assumed to be produced at scale. Again, costs are presented in 2020$. Key data for the cost of avoided GHG emissions are shown in Table 50 and Table 51 for midsize sedans and small SUVs, respectively, 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 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, registration, repair, and maintenance. It is important to emphasize the nature of the cost of avoided CO_2e as it relates to negative costs. Recall that the total avoided CO_2e is in the denominator, so a smaller quantity of avoided CO_2e will increase the negative cost compared to a larger reduction.

Lifetime costs versus GHG emissions for the FUTURE TECHNOLOGY case of midsize sedans are shown in Figure 39 (lifetime) and Figure 40 (first owner perspective), and those for SUVs are shown in Figure 41 (lifetime) and Figure 42 (first owner perspective). These figures present GHG emissions over the noted time frame on the primary x-axis, and the percent reduction compared to the conventional gasoline vehicle on the secondary x-axis. The lifetime vehicle cost is shown on the y-axis. The results indicate opportunities to reduce GHG emissions with all powertrains as well the opportunity to reduce cost for select cases. Modeled costs of avoided GHG emissions for the FUTURE TECHNOLOGY case, considering the full 15-year vehicle lifetime are below \$500/tonne CO_2e for all cases shown. The BEV400 and FCEV pathways are markedly different from the CURRENT TECHNOLOGY case. The cost of those technologies, though still a major component of overall vehicle cost, is modeled to improve significantly over the intervening period, leading to a much lower total vehicle cost.

For the FUTURE TECHNOLOGY case, HEV, PHEV, and BEV platforms offer the lowest modeled costs of avoided GHG emissions, with many options having a negative cost (i.e., the cost is less than that of the gasoline ICEV). FCEVs offer lower cost GHG emissions opportunities than ICEV technologies, except for the CNG vehicle operating on RNG.

As in the FUTURE TECHNOLOGY case, the sensitivity case of 3-year ownership (shown in Figure 40 and Figure 42) shows modeled costs that are typically higher than those for the 15-year full vehicle lifetime. There are some exceptions to this rule, such as HEVs operating on e-fuels. This is because the HEV purchase cost is less than the gasoline turbo ICEV, but its fuel costs are greater. The 3-year ownership costs of avoided GHG emissions range from -\$500 to \$1,500/tonne CO_2e in the FUTURE TECHNOLOGY case.

Table 52 and Table 53 summarize the cost of avoided GHG emissions results for all CURRENT TECHNOLOGY and FUTURE TECHNOLOGY vehicle-fuel pathways for midsize sedans and small SUVs, respectively. Note the limitations of the GHG abatement cost metric "\$/tonne CO_2e avoided" shown in Table 52 and Table 53. 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 not considered here.

Table 50. Costs and GHG emissions for the FUTURE TECHNOLOGY midsize sedan case

Base Case (5% discount rate, mid-point fuel cost)		**Vehicle Cost (2020$)**	**Fuel Cost ($/gge)**	**Vehicle F/E (mpgge)**	**GHG Emissions (g CO_2e/mi)**	**3-year Cost ($/mi)**	**15-year Cost ($/mi)**
Vehicle	**Fuel**						
Gasoline	Conv.	29,210	2.37	41.5	288	0.45	0.29
Gasoline	Pyr.	29,210	3.60	41.5	99	0.48	0.32
Gasoline	E-fuels (nuclear)	29,210	5.19	41.5	59	0.52	0.36
Gasoline	E-fuels (renewable)	29,210	5.19	41.5	45	0.52	0.36
E85	Corn Stover	29,210	3.87	41.5	116	0.49	0.32
Diesel	Conv.	30,940	2.47	41.3	293	0.48	0.30
Diesel	E-fuels (nuclear)	30,940	5.19	41.3	61	0.54	0.37
Diesel	E-fuels (renewable)	30,940	5.19	41.3	47	0.54	0.37
CNG	Conv.	32,864	1.44	36.9	263	0.48	0.30
CNG	RNG	32,864	1.85	36.9	76	0.50	0.31
HEV	Conv. Gasoline	27,870	2.37	56.0	222	0.42	0.26
HEV	Corn Stover	27,870	3.87	56.0	94	0.45	0.29
HEV	Pyr.	27,870	3.60	56.0	82	0.44	0.28
HEV	E-fuels (nuclear)	27,870	5.19	56.0	52	0.47	0.31
HEV	E-fuels (renewable)	27,870	5.19	56.0	41	0.47	0.31
PHEV50	Pyr. + NG ACC	29,908	3.60/3.51	60.3/119.6	144	0.45	0.28
PHEV50	Pyr. + NG ACC w/ CCS	29,908	3.60/4.04	60.3/119.6	75	0.45	0.28
PHEV50	Pyr. + Wind	29,908	3.60/4.77	60.3/119.6	52	0.45	0.28
PHEV50	Pyr. + Solar PV	29,908	3.60/4.76	60.3/119.6	52	0.45	0.28
FCEV300	LT Elec. Wind/Solar	32,697	4.00	80.3	53	0.49	0.31
FCEV300	NG SMR w/ CCS	32,697	4.00	80.3	67	0.49	0.31
FCEV400	LT Elec. Wind/Solar	33,370	4.00	79.3	56	0.50	0.31
FCEV400	NG SMR w/ CCS	33,370	4.00	79.3	70	0.50	0.31
BEV200	2035 Avg U.S. Grid	26,145	4.10	148.5	121	0.38	0.23
BEV200	Wind	26,145	4.77	148.5	37	0.39	0.24
BEV300	2035 Avg U.S. Grid	28,315	4.10	144.5	129	0.41	0.25
BEV300	Wind	28,315	4.77	144.5	42	0.42	0.26
BEV400	2035 Avg U.S. Grid	31,683	4.10	133.3	144	0.46	0.28
BEV400	Wind	31,683	4.77	133.3	49	0.46	0.29

Table 51. Costs and GHG emissions for the FUTURE TECHNOLOGY small SUV case

Base Case (5% discount rate, mid-point fuel cost)		**Vehicle Cost (2020$)**	**Fuel Cost ($/gge)**	**Vehicle F/E (mpgge)**	**GHG Emissions (g CO_2e/mi)**	**3-year Cost ($/mi)**	**15-year Cost ($/mi)**
Vehicle	**Fuel**						
Gasoline	Conv.	31,305	2.37	37.3	323	0.49	0.31
Gasoline	Pyr.	31,305	3.60	37.3	113	0.52	0.34
Gasoline	E-fuels (nuclear)	31,305	5.19	37.3	69	0.56	0.39
Gasoline	E-fuels (renewable)	31,305	5.19	37.3	53	0.56	0.39
E85	Corn stover	31,305	3.87	37.3	132	0.53	0.35
Diesel	Conv.	33,034	2.47	39.0	316	0.51	0.32
Diesel	E-fuels (nuclear)	33,034	5.19	39.0	69	0.58	0.39
Diesel	E-fuels (renewable)	33,034	5.19	39.0	54	0.58	0.39
CNG	Conv.	34,958	1.44	33.1	296	0.52	0.32
CNG	RNG	34,958	1.85	33.1	88	0.53	0.33
HEV	Conv. Gasoline	30,516	2.37	48.9	256	0.46	0.29
HEV	Corn Stover	30,516	3.87	48.9	110	0.49	0.32
HEV	Pyr.	30,516	3.60	48.9	96	0.49	0.31
HEV	E-fuels (nuclear)	30,516	5.19	48.9	62	0.52	0.35
HEV	E-fuels (renewable)	30,516	5.19	48.9	49	0.52	0.35
PHEV50	Pyr. + NG ACC	32,603	3.60/3.51	50./99.4	174	0.49	0.31
PHEV50	Pyr. + NG ACC w/ CCS	32,603	3.60/4.04	50./99.4	91	0.49	0.31
PHEV50	Pyr. + Wind	32,603	3.60/4.77	50./99.4	63	0.50	0.31
PHEV50	Pyr. + Solar PV	32,603	3.60/4.76	50./99.4	63	0.50	0.31
FCEV300	LT Elec. Wind/Solar	36,683	4.00	66.1	64	0.56	0.35
FCEV300	NG SMR w/ CCS	36,683	4.00	66.1	81	0.56	0.35
FCEV400	LT Elec. Wind/Solar	37,625	4.00	65.2	67	0.57	0.36
FCEV400	NG SMR w/ CCS	37,625	4.00	65.2	85	0.57	0.36
BEV200	2035 Avg U.S. Grid	29,354	4.10	120.6	148	0.43	0.27
BEV200	Wind	29,354	4.77	120.6	44	0.44	0.27
BEV300	2035 Avg U.S. Grid	32,211	4.10	117.2	158	0.47	0.29
BEV300	Wind	32,211	4.77	117.2	51	0.48	0.30
BEV400	2035 Avg U.S. Grid	35,948	4.10	109.2	174	0.52	0.32
BEV400	Wind	35,948	4.77	109.2	59	0.53	0.33

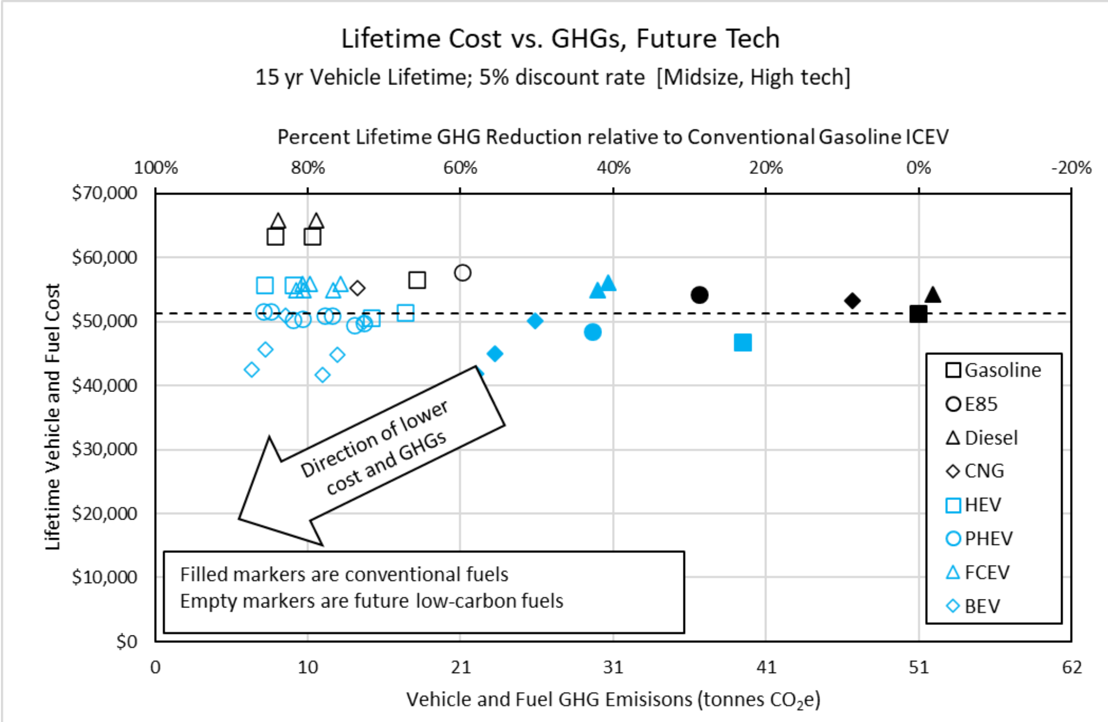

Figure 39. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY midsize sedan case for the FUTURE TECHNOLOGY case over its lifetime

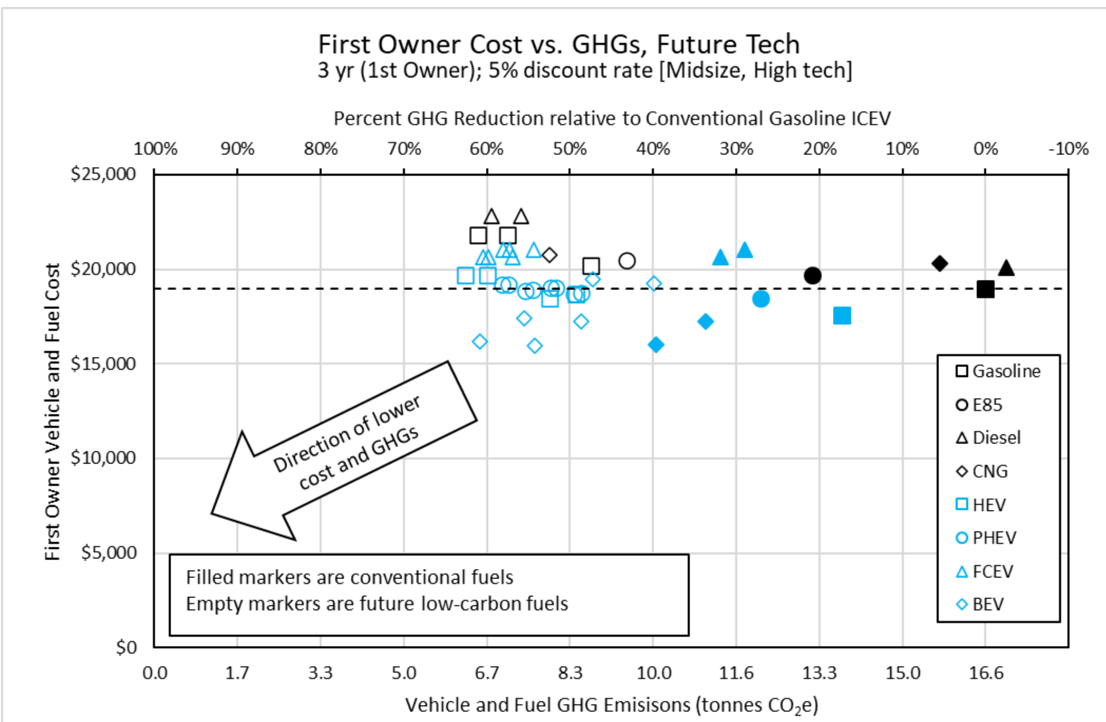

Figure 40. First owner costs versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY midsize sedan case for the FUTURE TECHNOLOGY case during the first owner

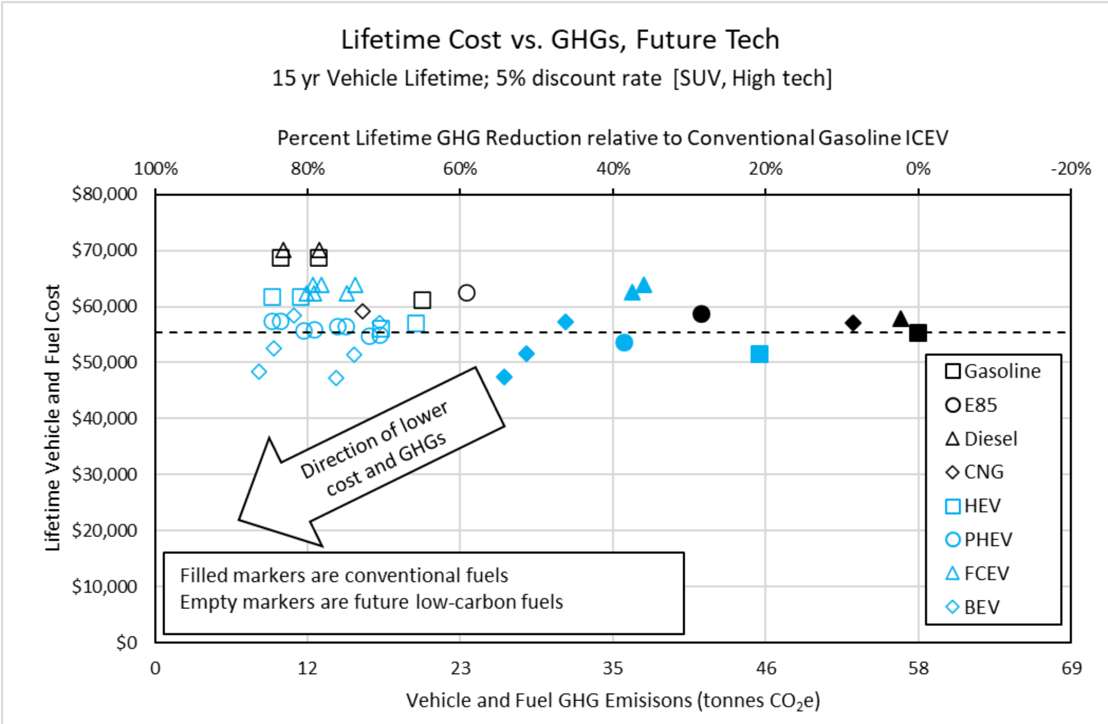

Figure 41. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY small SUV case for the FUTURE TECHNOLOGY case over its lifetime

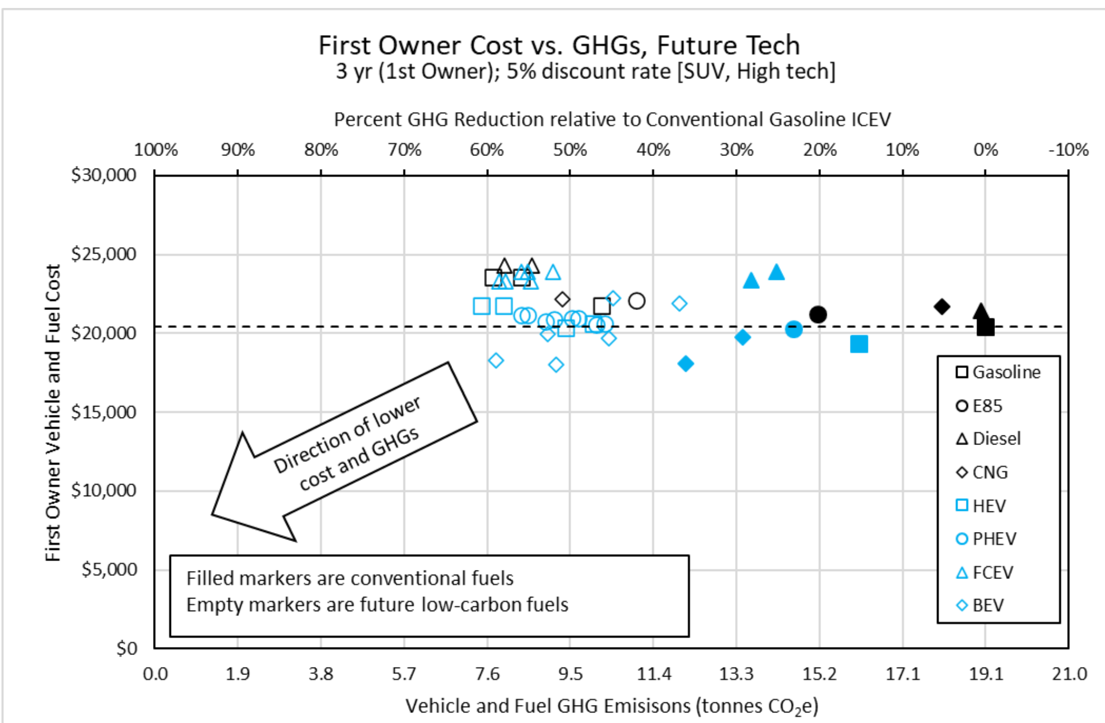

Figure 42. First owner costs versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY small SUV case for the FUTURE TECHNOLOGY case during the first owner

Table 52. Cost of avoided GHG emissions for CURRENT TECHNOLOGY and FUTURE TECHNOLOGY midsize sedan cases, relative to their respective gasoline ICEVs

Cost of Avoided GHG Emissions Summary, Base Case (5% discount rate, mid-point 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 Case				
E85 - Corn	19.8	120	4.7	120
Diesel - Conventional	4.7	1,110	0.9	2,560
CNG - CNG	6.7	1,480	1.3	2,970
HEV - Conventional Gasoline	20.2	140	4.7	350
PHEV50 - Conventional Gasoline	28.9	400	5.2	980
FCEV300 - NG SMR	31.4	1,250	7.0	2,020
FCEV400 - NG SMR	30.4	1,370	6.4	2,370
BEV200 - 2020 Avg U.S. Grid Mix	38.4	150	7.5	390
BEV300 - 2020 Avg U.S. Grid Mix	35.4	450	5.3	1,330
BEV400 - 2020 Avg U.S. Grid Mix	30.6	970	2.3	5,420
FUTURE TECHNOLOGY Case				
Gasoline - Pyr.	33.7	160	7.9	160
Gasoline - E-fuels (nuclear)	40.7	300	9.6	300
Gasoline - E-fuels (renewable)	43.2	280	10.2	280
E85 - Corn stover	30.6	210	7.2	210
Diesel - Conv.	-1.0	-2,900	-0.4	-2,510
Diesel - E-fuels (nuclear)	40.4	360	9.3	410
Diesel - E-fuels (renewable)	43.0	340	9.9	390
CNG - Conv.	4.4	440	0.9	1,470
CNG - RNG	37.7	100	8.7	200
HEV - Conv. Gasoline	11.8	-380	2.9	-480
HEV - Corn Stover	34.5	10	8.2	-30
HEV - Pyr.	36.7	-20	8.7	-50
HEV - E-fuels (nuclear)	42.0	110	10.0	70
HEV - E-fuels (renewable)	43.9	100	10.4	70
PHEV50 - Pyr. + NG ACC	25.6	-70	5.4	-50
PHEV50 - Pyr. + NG ACC w/ CCS	37.9	-50	8.2	-30
PHEV50 - Pyr. + Wind	42.0	-20	9.2	-10
PHEV50 - Pyr. + Solar PV	42.0	-20	9.2	-10
FCEV300 - LT Elec. wind/solar	41.8	90	10.1	170
FCEV300 - NG SMR w/ CCS	39.3	90	9.5	180
FCEV400 - LT Elec. wind/solar	41.3	110	9.6	220
FCEV400 - NG SMR w/ CCS	38.8	120	9.0	230
BEV200 - 2035 Avg U.S. Grid	29.7	-320	6.6	-450
BEV200 - Wind	44.8	-200	10.1	-270
BEV300 - 2035 Avg U.S. Grid	28.4	-220	5.6	-300
BEV300 - Wind	43.9	-130	9.2	-160
BEV400 - 2035 Avg U.S. Grid	25.7	-50	3.9	80
BEV400 - Wind	42.5	-10	7.9	70

Table 53. Cost of avoided GHG emissions for CURRENT TECHNOLOGY and FUTURE TECHNOLOGY small SUV cases, relative to their respective gasoline ICEVs

Cost of Avoided GHG Emissions Summary, Base Case (5% discount rate, mid-point 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 Case				
E85 - Corn	22.1	120	5.2	120
Diesel - Conventional	5.9	860	1.2	1,940
CNG - CNG	8.0	1,410	1.6	2,780
HEV - Conventional Gasoline	20.9	190	4.9	450
PHEV50 - Conventional Gasoline	29.4	490	5.1	1,240
FCEV300 - NG SMR	32.0	1,580	7.1	2,570
FCEV400 - NG SMR	30.8	1,740	6.3	3,060
BEV200 - 2020 Avg U.S. Grid Mix	40.3	260	7.6	640
BEV300 - 2020 Avg U.S. Grid Mix	36.9	610	5.1	1,880
BEV400 - 2020 Avg U.S. Grid Mix	31.0	1,280	1.4	11,960
FUTURE TECHNOLOGY Case				
Gasoline - Pyr.	37.5	160	8.8	160
Gasoline - E-fuels (nuclear)	45.3	300	10.6	300
Gasoline - E-fuels (renewable)	48.1	280	11.3	280
E85 - Corn stover	34.1	210	8.0	210
Diesel - Conv.	1.3	1,840	0.1	11,070
Diesel - E-fuels (nuclear)	45.2	330	10.4	370
Diesel - E-fuels (renewable)	47.9	310	11.0	350
CNG - Conv.	4.9	330	1.0	1,250
CNG - RNG	42.0	90	9.7	180
HEV - Conv. Gasoline	12.0	-320	2.9	-370
HEV - Corn Stover	38.0	40	9.0	20
HEV - Pyr.	40.6	20	9.6	0
HEV - E-fuels (nuclear)	46.6	140	11.1	120
HEV - E-fuels (renewable)	48.8	130	11.6	120
PHEV50 - Pyr. + NG ACC	26.7	-20	5.5	30
PHEV50 - Pyr. + NG ACC w/ CCS	41.4	-10	8.9	20
PHEV50 - Pyr. + Wind	46.4	10	10.1	40
PHEV50 - Pyr. + Solar PV	46.4	10	10.1	40
FCEV300 - LT Elec. wind/solar	46.2	150	11.2	260
FCEV300 - NG SMR w/ CCS	43.1	160	10.4	280
FCEV400 - LT Elec. wind/solar	45.6	190	10.7	330
FCEV400 - NG SMR w/ CCS	42.5	200	9.9	350
BEV200 - 2035 Avg U.S. Grid	31.2	-260	6.9	-340
BEV200 - Wind	49.8	-140	11.2	-190
BEV300 - 2035 Avg U.S. Grid	29.5	-130	5.6	-120
BEV300 - Wind	48.6	-60	10.1	-40
BEV400 - 2035 Avg U.S. Grid	26.6	70	3.7	420
BEV400 - Wind	47.1	60	8.5	210

10.4. SENSITIVITY ANALYSIS CASES

The base case modeling used for the LCD analysis (Section 9) and the cost of avoided GHG emissions metric (this section) is based on reference (base case) vehicle and fuel costs. The base case modeling assumes a discount rate of 5%. The FUTURE TECHNOLOGY case vehicle cost modeling includes low and high vehicle costs for each platform. Similarly, for the FUTURE TECHNOLOGY case, many of the fuels include low and high fuel costs (e.g., E85 from corn stover and fuels based on AEO 2021 projections). Additionally, for both the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, the cost analysis includes sensitivity analyses using 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 case are shown in Figure 43 Figure 44 for midsize sedans and small SUVs, respectively. FUTURE TECHNOLOGY cases are shown in Figure 45 and Figure 46 for midsize sedans and small SUVs, respectively. Note also that uncertainty bars are shown for all FUTURE TECHNOLOGY pathways, based on the effect of the range of high and low fuel costs.

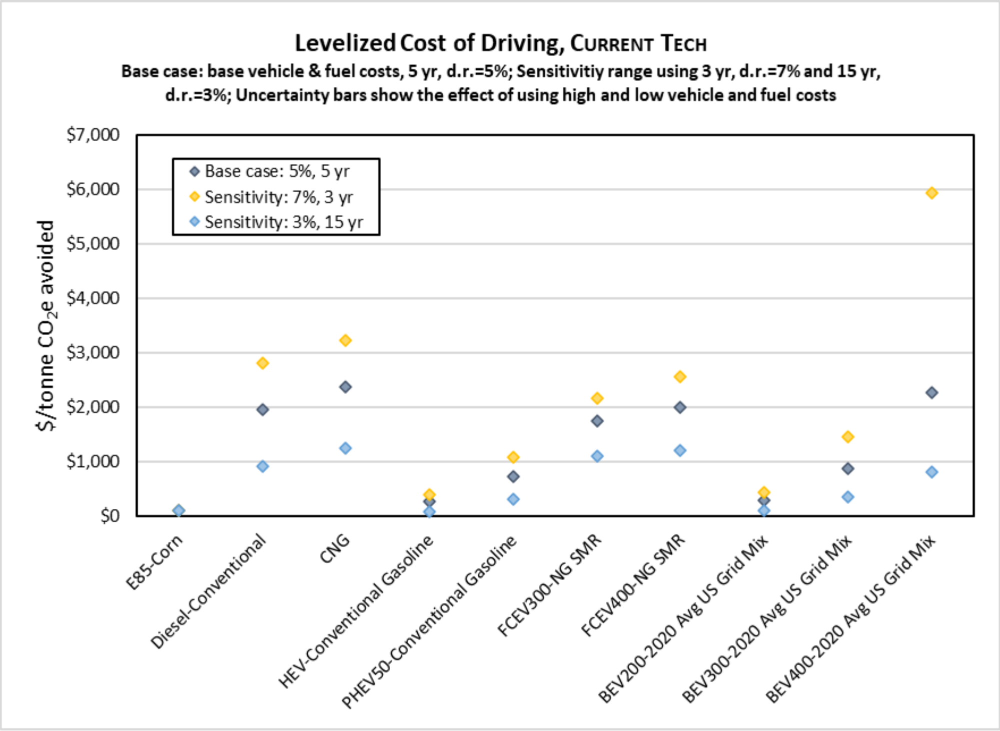

Figure 43. Range of avoided GHG emissions results using 3 different analysis frameworks (see text) for the Current Technology midsize sedan case

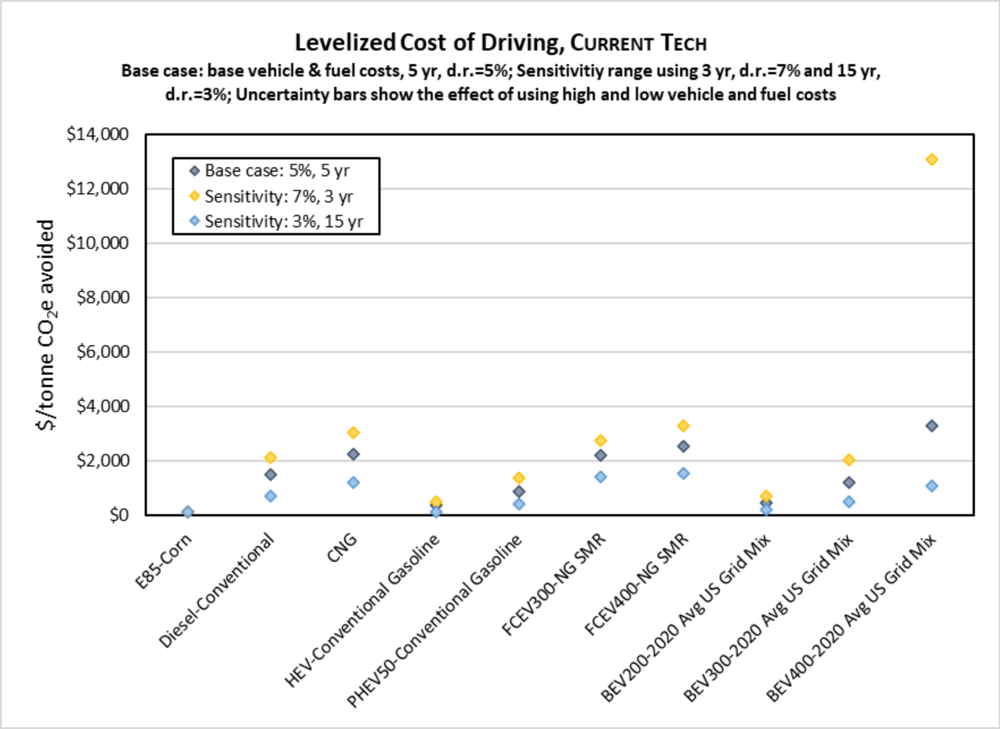

Figure 44. Range of avoided GHG emissions results using 3 different analysis frameworks (see text) for the Current Technology small SUV case

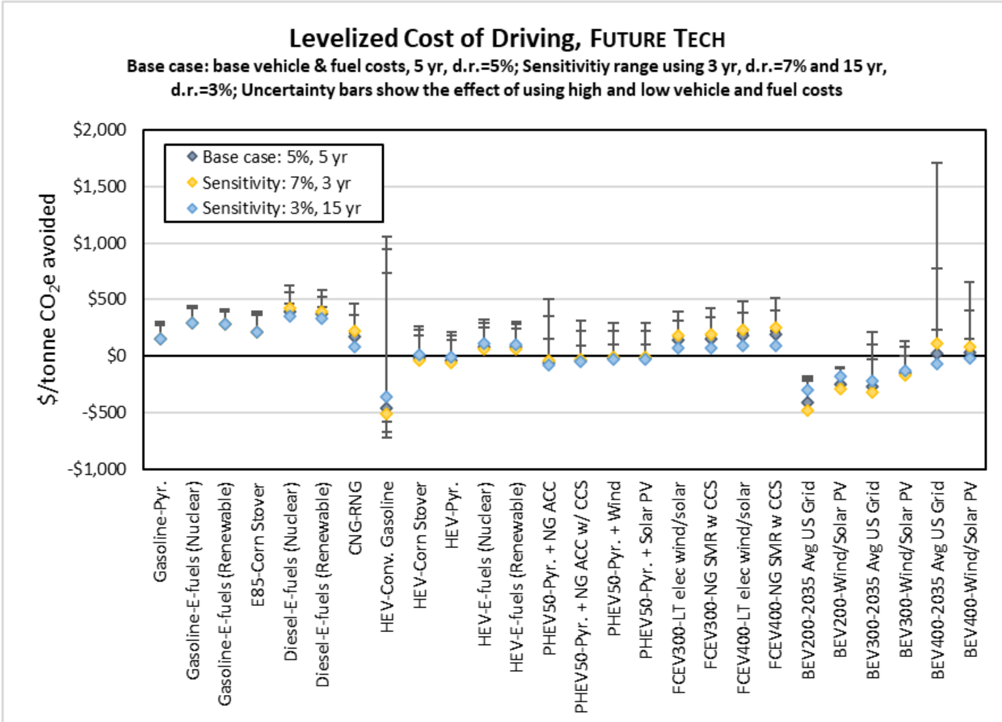

Figure 45. Range of avoided GHG emissions results using 3 different analysis frameworks (see text) for the FUTURE TECHNOLOGY midsize sedan case

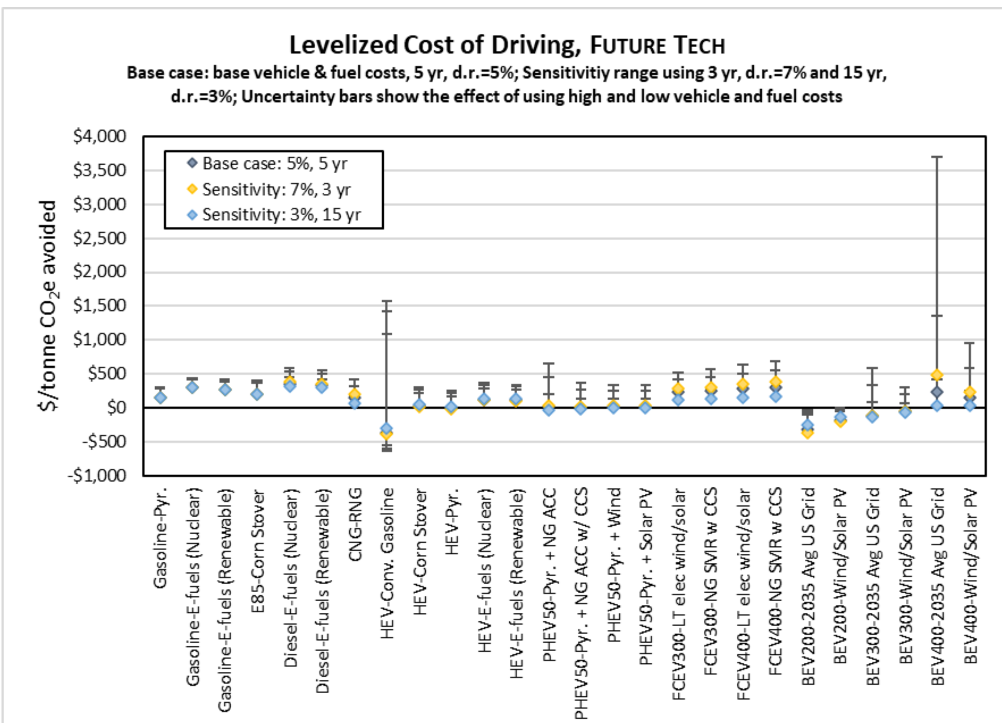

Figure 46. Range of avoided GHG emissions results using 3 different analysis frameworks (see text) for the FUTURE TECHNOLOGY case small SUV case

11. LIMITATIONS AND FUTURE IMPLICATIONS

While climate change is of increasing global concern, and thus requires life cycle 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 the 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. Other sustainability metrics include water availability and use, energy security, and environmental justice.

Challenges, such as infrastructure availability for certain fuels (e.g., hydrogen fueling stations) require more careful analysis. The market demand for fuels and vehicles depends strongly on their costs, which this study attempted to evaluate quantitatively. However, other factors that impact consumer choice are not covered in this study (such as vehicle range, battery charging time, and hydrogen fuel/charge availability). Furthermore, the cost estimates in this study are subject to uncertainties and their dependence 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 HRD, FTD), and current prices reported by the Energy Information Administration, 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.

Finally, this study evaluated GHG emissions and cost of individual pathways and assumed common vehicle platforms for comparison. However, market scenario analysis is important to explore the realistic ramp up 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 sustainability factors 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, 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, vehicle and fuel costs, carbon abatement costs, and technology feasibility in this report are summarized below.

Emissions

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

Costs

- FUTURE TECHNOLOGY costs for advanced technologies reduce faster than incumbent technologies compared to their CURRENT TECHNOLOGY counterparts, 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. 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.
- Several vehicles (HEV, PHEV, and BEVs) in the Future Technology case had lower costs *and* lower GHG emissions than the conventional gasoline ICEV.

Costs of Carbon Abatement

- For the CURRENT TECHNOLOGY 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 carbon abatement costs vary significantly by technology and fuel pathway, with several pathways, mostly electric vehicle, that are below zero (i.e., there is a cost reduction for carbon abatement). The pathways that do have a carbon abatement cost are generally 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: Price and Efficiency Comparison of Modeled and Real-World Vehicles

This appendix details the price and efficiency of midsize and small SUV vehicles currently on the retail market for Model Year 2020 and compares them to those modeled through Autonomie 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.

Figure A.1. below shows the trend line of adjusted fuel economy (EPA sticker value) on combined cycle vs. vehicle MSRP of midsize conventional vehicles from model year 2020 in the market. It can be seen from the figure that the vehicle combination modeled by Autonomie is well aligned within the manufacturers with high share of volume in the market for both in terms of vehicle fuel economy as well as MSRP.

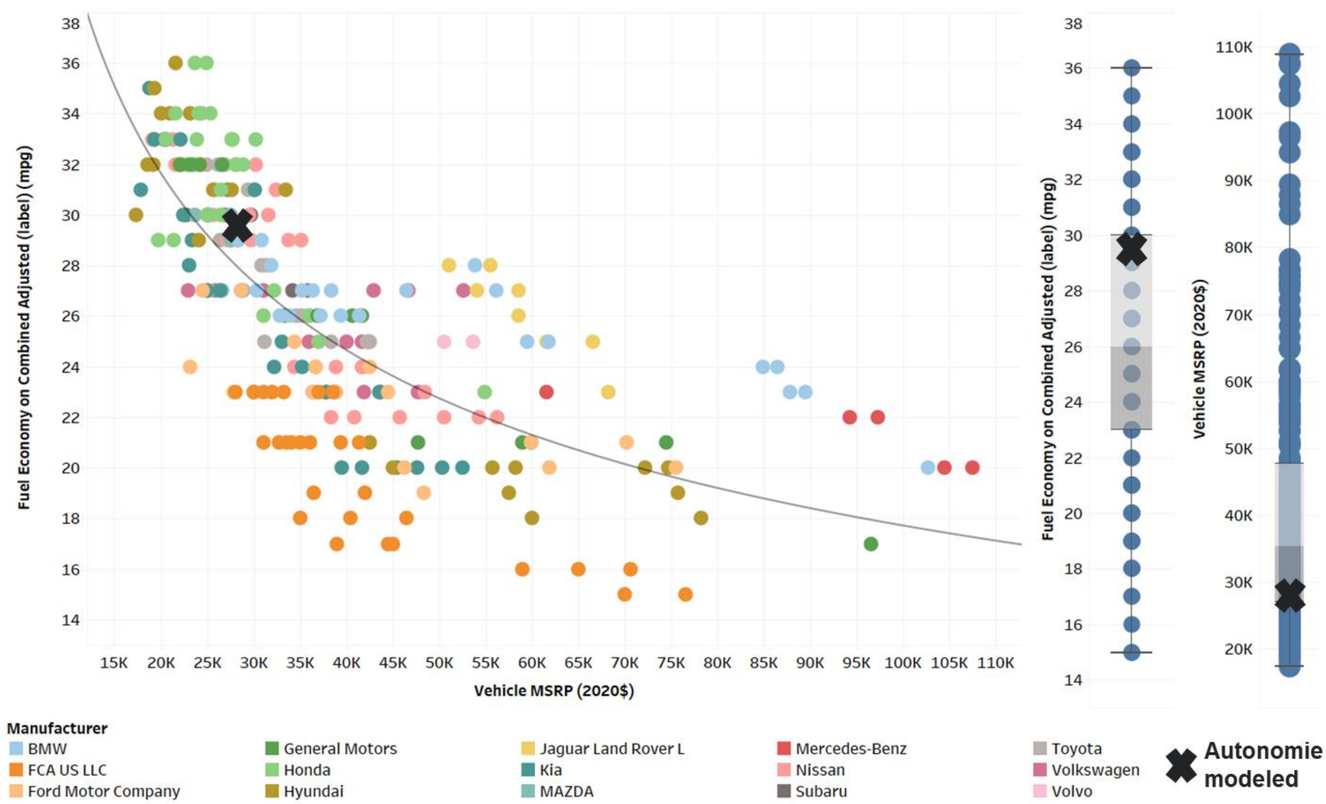

Figure A.1. Fuel Economy and Vehicle MSRP trend line of conventional midsize vehicles in the market from MY2020

Figure A.2. below shows the trend line of adjusted fuel economy on combined cycle vs. vehicle MSRP of small SUV conventional vehicles from model year 2020 in the market. Similar to the previous observation, the conventional small SUV combination modeled through Autonomie falls within the range of vehicle manufacturers with high market share in terms of both fuel economy as well as vehicle MSRP.

Figure A.2. Fuel Economy and Vehicle MSRP trend line of conventional small SUVs in the market from MY2020

The following subsection details the different parameter comparisons of the modeled vehicle in Autonomie against the vehicles with the top sales in the market fleet today. This detailed comparison is conducted across different vehicle powertrain types.

A.1 CONVENTIONAL SI TURBOCHARGED VEHICLES

Table A.1 shows the market analysis for Model Year 2020 midsize conventional turbocharged gasoline vehicles detailing the different vehicle characteristics against the combination modeled through Autonomie. And table A.2. details the same analysis against small SUV vehicle class.

Table A.1. Comparison of modeled midsize conventional turbocharged vehicle with vehicles of high sales in the market

Model Year	Make	Model	Engine Disp. (L)	Rated HP	# of Cylinders	Transmission Type	# of Gears	Equivalent Test Weight (kg)	UDDS Adjusted (mpg)	HWFET Adjusted (mpg)	Combined Adjusted (mpg)	MSRP $	Accel time 0-60mph (s)
2020	Honda	Accord	2	252	4	Automatic	10	1644	23	34	27	31060	7.6
2020	Kia	Optima	1.6	178	4	Automatic	7	1644	27	37	31	27190	6.9
2020	Ford	Fusion	1.5	169	4	Automatic	6	1701	23	34	27	28690	8.9
2020	Hyundai	Sonata	1.6	180	4	Automatic	8	1644	27	36	31	33500	7.3
2020	Chevrolet	Malibu	2	260	4	Automatic	9	1645	29	36	32	33320	8.2
2020	Mazda	Mazda 6	2.5	227	4	Automatic	6	1758	23	31	26	29800	7.9
2020	Vw	Passat	2	174	4	Automatic	6	1700	23	34	27	28645	7.8
MY20 Average		**Midsize**	**2**	**206**	**4**	**Automatic**	**6**	**1677**	**25**	**35**	**29**	**30315**	**8**
Autonomie		**Midsize**	**2**	**194**	**4**	**Automatic**	**6**	**1573**	**28.3**	**34.1**	**30.7**	**28630**	**7.9**

Table A.2. Comparison of modeled small SUV conventional turbocharged vehicle with vehicles of high sales in the market

Model Year	Make	Model	Engine Disp. (L)	Rated HP	# of Cylinders	Transmission Type	# of Gears	Equivalent Test Weight (lbs.)	UDDS Adjusted (mpg)	HWFET Adjusted (mpg)	Combined Adjusted (mpg)	MSRP$	Accel time 0-60mph (s)
2020	GM	Equinox FWD	1.5	170	4	Automatic	6	3625	26.4	30.7	28.2	28695	6.8
2020	FCA	Wrangler	2	270	4	Automatic	8	4250	20.8	22.4	21.5	40409	6.7
2020	Ford	Escape AWD	1.5	175	3	Automatic	8	3750	26.3	31.0	28.0	28350	8.4
2020	Mazda	CX-5	2.5	227	4	Automatic	6	4250	21.8	27.2	23.9	38255	8.3
2020	GM	Trax FWD	1.4	138	4	Semi-Automatic	6	3375	25.9	31.1	28.0	22295	9.3
MY20 Average		**Small SUV**	**1.8**	**196**	**4**	**Automatic**	**7**	**3850**	**24.2**	**28.5**	**25.9**	**31601**	**7.9**
Autonomie		**Small SUV**	**2**	**211**	**4**	**Automatic**	**6**	**3770**	**26**	**29.9**	**27.6**	**31664**	**8**

Across the two tables, it can be seen that there exists a close relationship of the modeled vehicles in Autonomie across all parameters of interest among the vehicles with high sales for both midsize and small SUV vehicle classes.

A.2 Full Hybrid Electric Vehicles (HEVs)

Table A.3 shows the market analysis for Model Year 2020 midsize full HEVs detailing the different vehicle characteristics against the combination modeled through Autonomie. And table A.4. details the same analysis against small SUV vehicle class.

Table A.3. Comparison of modeled midsize full HEVs with vehicles of high sales in the market

Model Year	Make	Model	Engine Disp. (L)	Rated HP	Equivalent Test Weight (lbs.)	UDDS Adjusted (mpg)	HWFET Adjusted (mpg)	Combined Adjusted (mpg)	Battery Voltage, (V)	Battery Energy Capacity, (Amp-hrs)	Motor1 Peak Power (kW)	Motor2 Peak Power (kW)	MSRP$	Accel time 0-60mph (s)
2020	Toyota	Prius	1.8	96	3375	54.5	49.7	52.2	207	4	53	23	26490	9.7
2020	Toyota	Prius AWD	1.8	96	3500	52.0	48.1	50.0	202	6.5	53	23	27890	9.7
2020	Toyota	Prius Eco	1.8	96	3250	57.8	53.3	55.7	207	4	53	23	25280	9.7
2020	Ford	Fusion (HEV)	2	141	4000	43.0	41.0	42.0	280	4.75	64		29195	9
2020	Toyota	Camry Hybrid LE	2.5	176	3750	51.0	52.7	51.8	259	4	88		29425	7.4
2020	Toyota	Camry Hybrid XLE	2.5	176	3875	44.2	47.0	46.2	259	4	88		33725	7.4
2020	Honda	Accord Hybrid	2	143	3625	47.8	47.3	47.6	259	4.25	135	104	26425	7.2
2020	Honda	Insight Touring	1.5	107	3375	51.2	44.5	48.0	222	5.5	96		29295	8.1
2020	Honda	Insight	1.5	107	3250	54.9	48.8	52.0	222	5.5	96		23885	8.1
2020	Hyundai	Sonata Hybrid Blue	2	150	3625	50.0	54.3	51.9	270	5.5	39		28745	6.8
2020	Hyundai	Sonata Hybrid	2	150	3750	44.6	50.9	47.2	270	5.5	39		30895	6.8
2020	Kia	Optima Hybrid	2	154	3875	39.7	44.9	41.9	270	6.5	38		30235	7.7
MY20 Average		**Midsize**	**2.0**	**133**	**3604**	**49.2**	**48.5**	**48.9**	**244**	**5.0**	**70**	**43.25**	**28457**	**8.1**
Autonomie		**Midsize**	**2.0**	**106**	**3611**	**49.7**	**44.7**	**47.3**	**238**	**6.5**	**79.5**	**61**	**32649**	**8.1**

Table A.4. Comparison of modeled small SUV full HEVs with vehicles of high sales in the market

Model Year	Make	Model	Engine Disp. (L)	Rated HP	# of Cylinders and Rotors	Equivalent Test Weight (lbs.)	UDDS Adjusted (mpg)	HWFET Adjusted (mpg)	Combined Adjusted (mpg)	Battery Voltage, (V)	Battery Energy Capacity, (Amp-hrs)	Motor1 Peak Power (kW)	Motor2 Peak Power (kW)	MSRP$	Accel time 0-60mph (s)
2020	Toyota	RAV4 XLE Hybrid	2.5	176	4	4000	41.0	38.2	40.2	245	6.5	88	40	30970	7.5
2020	Toyota	Highlander	2.5	186	4	4750	36.2	35.4	35.9	288	6.5	134	40	39375	7.2
2020	Kia	Niro	1.6	104	4	3625	50.9	46.3	48.7	240	6.5	32		25710	8.6
2020	Ford	Escape	2.5	162	4	3875	43.5	37.4	40.5	216	5	36		29510	8.7
2020	Lexus	Lexus UX	2	143	4	3875	43.0	40.9	42.1	216	6.5	80		35525	8.1
2020	Honda	CR-V	2	143	4	4000	40.4	35.0	38.2	266	5.3	135		30560	7.5
MY20 Average		**Small SUV**	**2.2**	**152**	**4**	**4021**	**42.5**	**38.9**	**40.9**	**245**	**6**	**84**	**40**	**31942**	**7.9**
Autonomie		**Small SUV**	**2.5**	**119**	**4**	**3929**	**43.6**	**38.4**	**41.0**	**281**	**7**	**93**	**69**	**36646**	**8.1**

For full HEVs, we observe a close relationship of the modeled vehicle in Autonomie against the vehicles in the fleet in terms of different aspects of vehicle characteristics. The same is held for both midsize and small SUV vehicle classes.

A.3 Battery Electric Vehicle

Table A.5 shows the market analysis for Model Year 2020 midsize BEVs detailing the different vehicle characteristics against the combination modeled through Autonomie. And Table A.6. details the same analysis against small SUV vehicle class.

Table A.5. Comparison of modeled midsize BEVs with vehicles of high sales in the market

Model Year	Make	Model	Equivalent Test Weight (lbs.)	CD UDDS Adjusted (kWh/100 mile)	CD HWFET Adjusted (kWh/100 mile)	CD Combined Adjusted (kWh/100 mile)	Adjusted Electricity Range (mile)	Battery Voltage, (V)	Battery Energy Capacity, (Amp-hrs)	Motor1 Peak Power (kW)	MSRP $	Accel Time 0-60mph (s)
2020	Tesla	Model 3 Long Range	4250	24.7	27.3	25.9	330	350	230	211	48190	5
2020	Tesla	Model 3 Standard Range RWD	3875	24.4	27.3	25.7	220	350	230	211	39190	5.6
2020	NISSAN	LEAF	3875	27.4	34.1	30.4	149	350	115	110	32525	8.4
2020	NISSAN	LEAF	4250	28.6	34.6	31.3	226	350	176	160	39125	7.4
2020	BMW	I3s	3375	27.1	33.1	29.8	153	352	120	125	45445	6.8
2020	Hyundai	Ioniq Electric	3750	23.3	27.9	25.4	170	319	120	100	34040	8.9
MY20 Average		**Midsize**	**3896**	**25.9**	**30.7**	**28.1**	**208**	**345**	**165**	**153**	**39753**	**7.0**
		Midsize BEV200	**3602**	**20.0**	**24.4**	**24.9**	**200**	**389**	**121**	**115**	**35457**	**8.0**
Autonomie		**Midsize BEV300**	**3918**	**20.9**	**25.7**	**26.1**	**301**	**396**	**188**	**125**	**43758**	**7.7**
		Midsize BEV400	**4037**	**24.1**	**27.4**	**29.2**	**396**	**410**	**268**	**137**	**54641**	**7.7**

Table A.6. Comparison of modeled small SUV BEVs with vehicles of high sales in the market

Model Year	Make	Model	Equivalent Test Weight (lbs.)	CD UDDS Adjusted (kWh/100mile)	CD HWFET Adjusted (kWh/100mile)	CD Combined Adjusted (kWh/100mile)	Adjusted Electricity Range (mile)	Battery Voltage, (V)	Battery Energy Capacity, (Amp-hrs)	Motor1 Peak Power (kW)	Motor2 Peak Power (kW)	MSRP$	Accel Time 0-60mph (s)
2020	Chevrolet	Bolt EV	3875	26.5	31.3	28.7	259	400	188.5	150		37495	8.4
2020	Tesla	Model Y Long Range AWD	4750	26.5	29.5	27.9	316	350	230	158	203	49990	4.1
2020	Hyundai	Kona Electric	4000	24.6	31.0	27.5	258	356	180	150		38365	7.6
2020	Kia	Niro Electric	4250	27.4	33.2	30.0	239	356	180	150		40210	7.5
MY20 Average		**Small SUV**	**4219**	**26.3**	**31.2**	**28.5**	**268**	**366**	**195**	**152**		**41515**	**6.9**
Autonomie		**Small SUV BEV200**	**3997**	**26.9**	**34.8**	**30.5**	**201**	**317**	**182**	**183**		**42137**	**8.0**
		Small SUV BEV300	**4365**	**28.2**	**36.5**	**31.9**	**297**	**373**	**243**	**199**		**51742**	**7.7**
		Small SUV BEV400	**4888**	**32.7**	**38.8**	**35.5**	**397**	**410**	**332**	**221**		**65409**	**7.7**

Across the two tables, it can be seen that there exists a close relationship of the modeled vehicles in Autonomie across all parameters of interest among the vehicles with high sales for both midsize and small SUV vehicle classes.

A.4 Fuel Cell vehicles

Table A.7 shows the market analysis for Model Year 2020 midsize fuel cell vehicles detailing the different vehicle characteristics against the combination modeled through Autonomie.

Table A.7. Comparison of modeled midsize fuel cell vehicles with vehicles of high sales in the market

Model Year	Make	Model	Equivalent Test Weight (lbs.)	UDDS Adjusted (mpg)	HWFET Adjusted (mpg)	Combined Adjusted (mpg)	Fuel Range (mile)	Battery Voltage, (V)	Battery Energy Capacity, (Amp-hrs)	Motor Peak Power (kW)	Fuel Cell Peak Power (kW)	MSRP $	Accel Time 0-60mph (s)
2020	Honda	Clarity	4500	68.0	67.0	68.0	360	346	4.25	130	103	58490	9
2020	Toyota	Mirai	4250	67.0	67.0	67.0	312	245	6.5	113	114	58550	9
MY20 Average			**4375**	**68**	**67**	**68**	**336**	**296**	**5**	**122**	**109**	**58520**	**9**
Autonomie		**Midsize 300**	**3622**	**61**	**75**	**66**	**286**	**238**	**6.5**	**115**	**85**	**49591**	**8.0**
		Midsize 400	**3715**	**59**	**74**	**65**	**381**	**238**	**6.5**	**118**	**88**	**51085**	**8.0**

For fuel cell vehicles, we observe a close relationship of the modeled vehicle in Autonomie against the midsize vehicles in the fleet in terms of different aspects of vehicle characteristics

Appendix B: 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. Figure B.1–Figure B.4 offer a breakdown of total life cycle emissions by feedstock, fuel, tailpipe, and vehicle manufacturing for small SUVs. Figure B.5– Figure B.8 offer a breakdown of total life cycle emissions by feedstock, fuel, tailpipe, and vehicle manufacturing for small SUVs. Bars extending below the axis represent reductions in the total GHG emissions due to biogenic CO_2 in the fuel offsetting the tailpipe emissions. Note that some pathways (E85, pyrolysis, and e-fuels) do not have the fuel cycles partitioned, rather those are the cumulative quantities and are grouped together in the vehicle operation category.

Figure B.9 and Figure B.10 show the GHG emissions associated with vehicle manufacturing cycle in tonnes of CO_2e for each midsize vehicle technology for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, respectively. While Figure B.11 and B.12 show the same for each small SUV vehicle technology for the CURRENT TECHNOLOGY and FUTURE TECHNOLOGY cases, respectively.

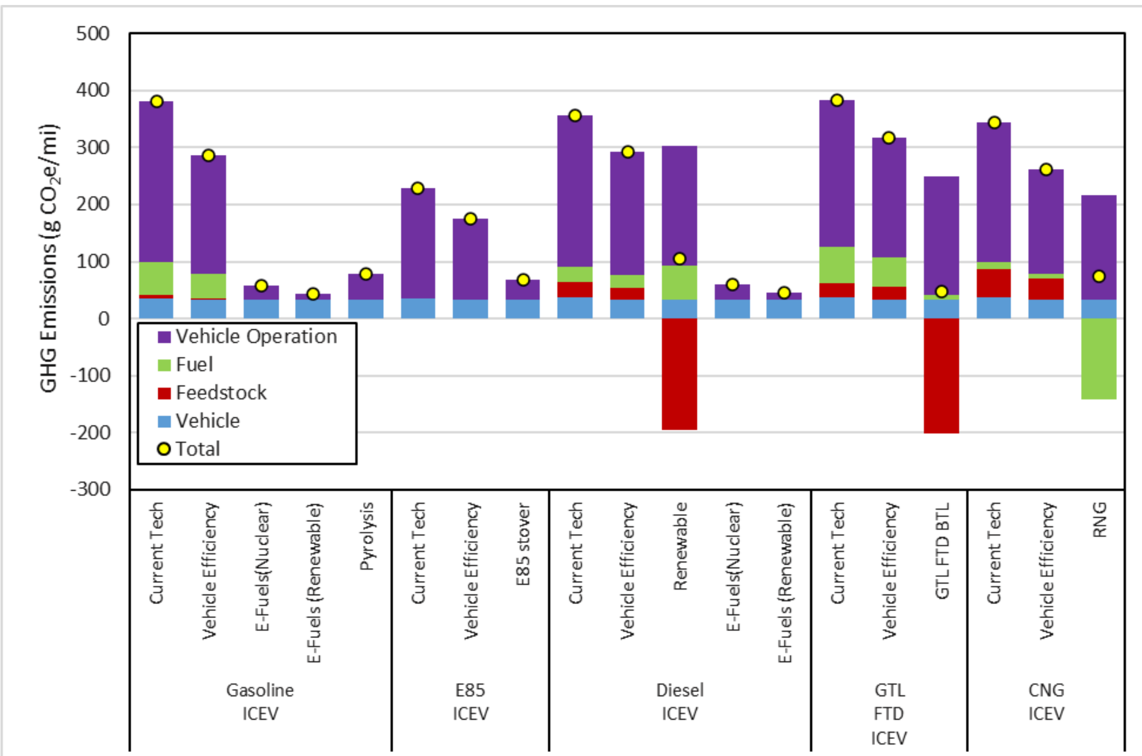

Figure B.1. Emissions for E85 ICEV, Diesel ICEV, GTL FTD ICEV, and CNG ICEV compared with midsize gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

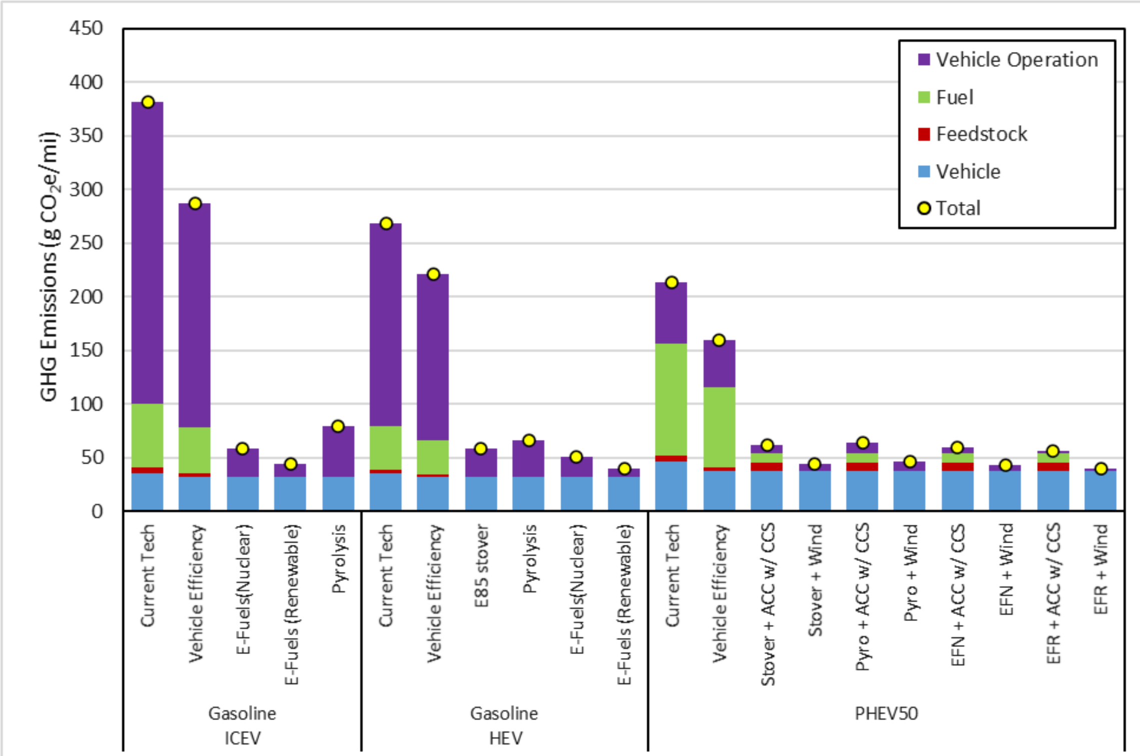

Figure B.2. Emissions for gasoline HEVs, and gasoline PHEVs compared with midsize gasoline ICEV Current Technology and vehicle efficiency gains

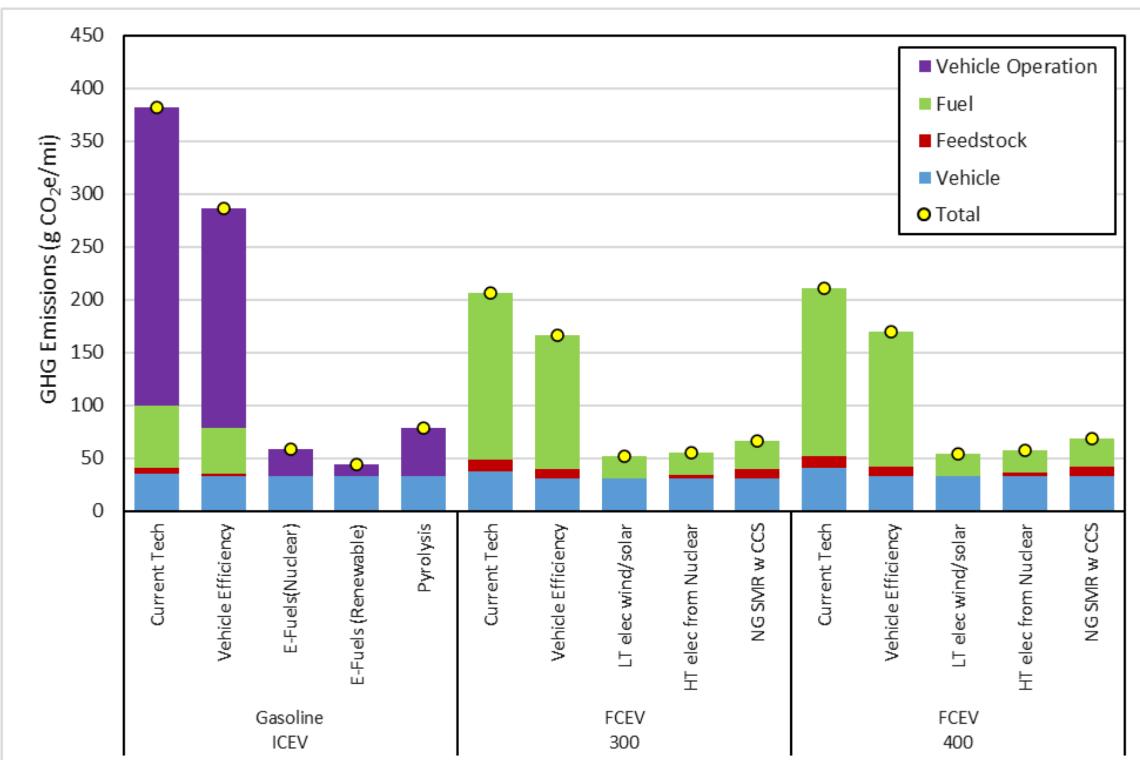

Figure B.3. Emissions for FCEV300 and FCEV400 compared with midsize gasoline ICEV Current Technology and vehicle efficiency gains

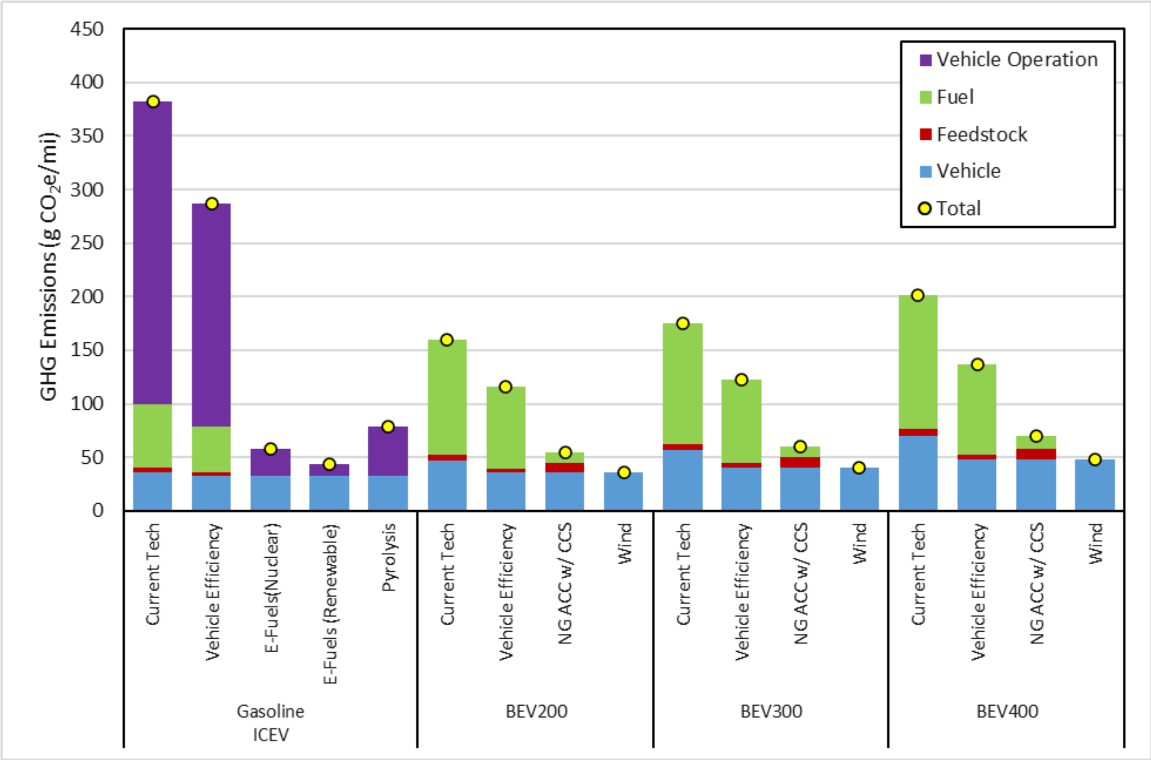

Figure B.4. Emissions for BEV200, BEV300, and BEV400 compared with midsize gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

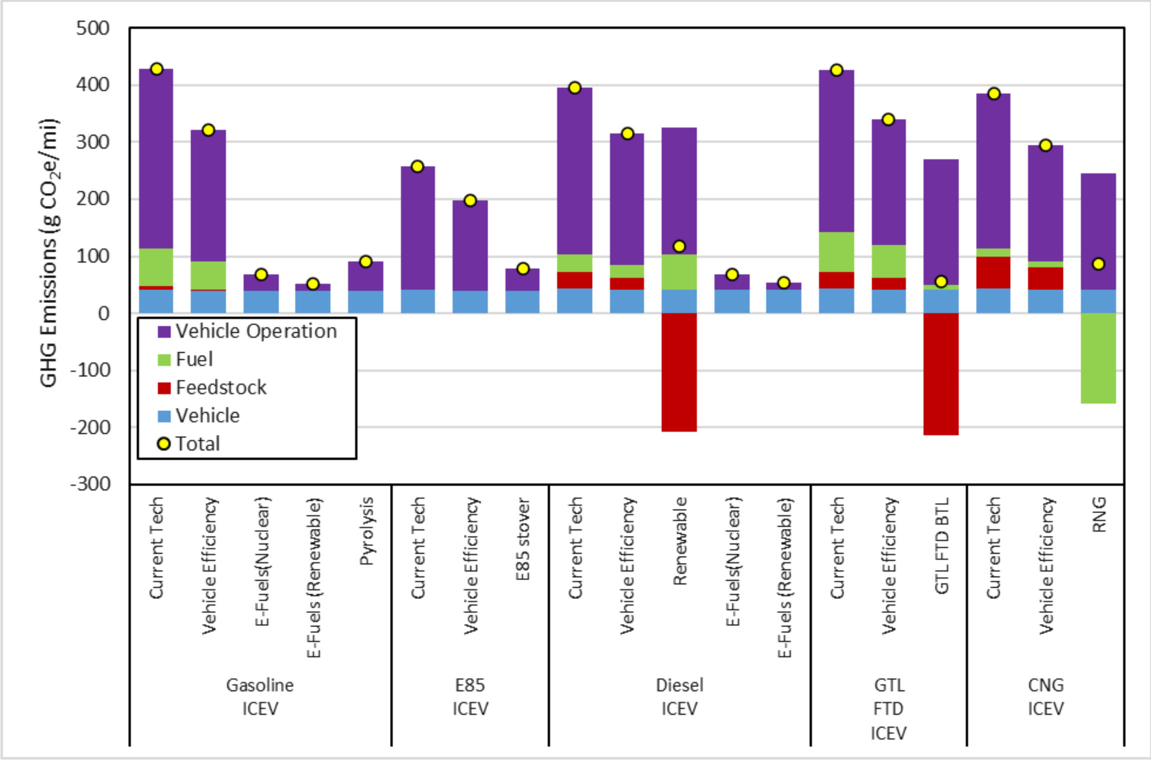

Figure B.5. Emissions for E85 ICEV, Diesel ICEV, GTL FTD ICEV, and CNG ICEV compared with small SUV gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

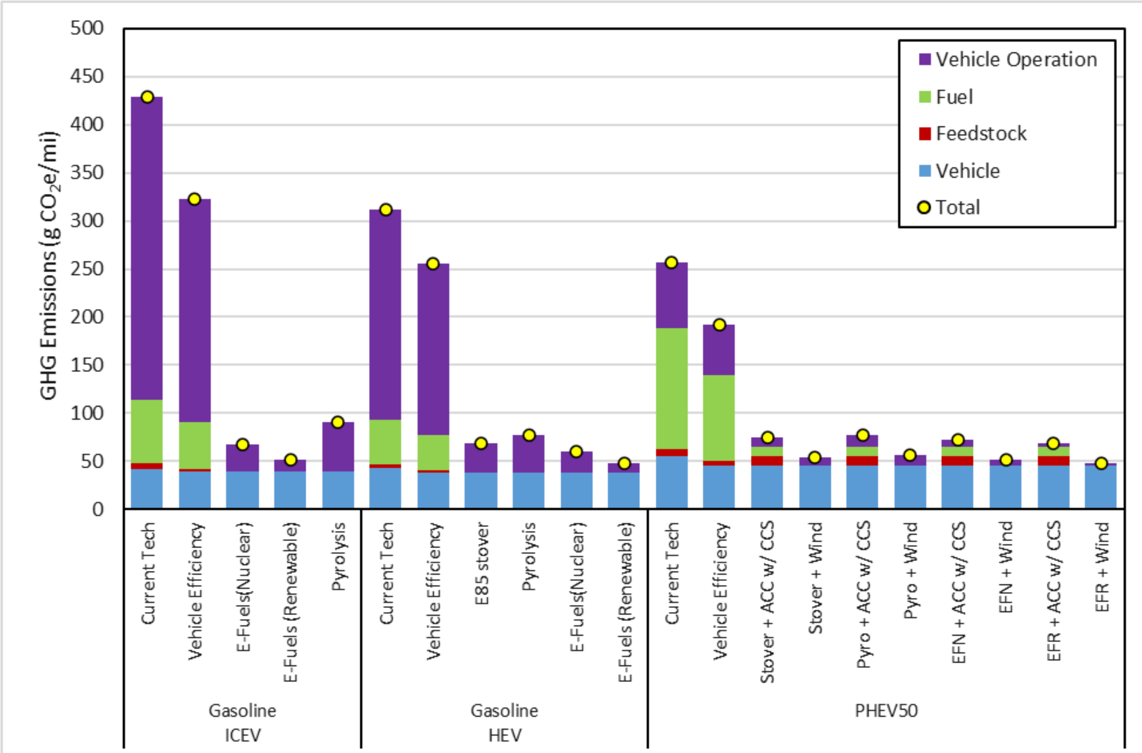

Figure B.6. Emissions for gasoline HEVs, and gasoline PHEVs compared with small SUV gasoline ICEV Current Technology and vehicle efficiency gains

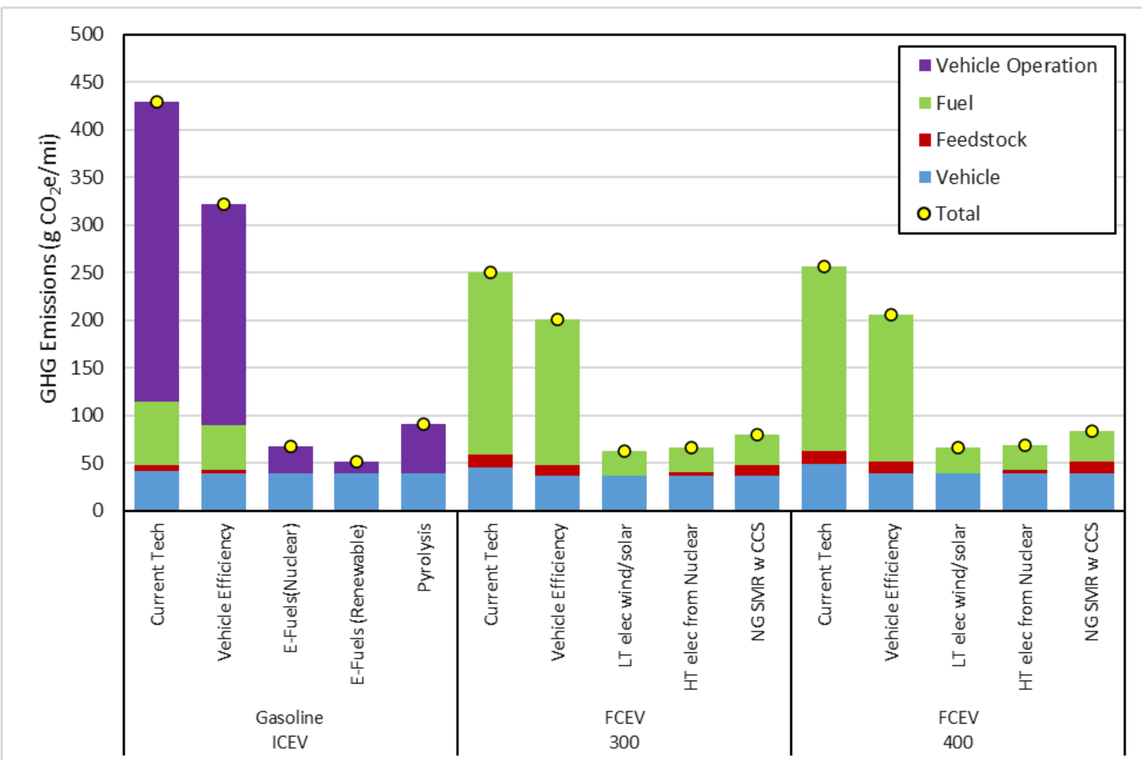

Figure B.7. Emissions for FCEV300 and FCEV400 compared with small SUV gasoline ICEV Current Technology and vehicle efficiency gains

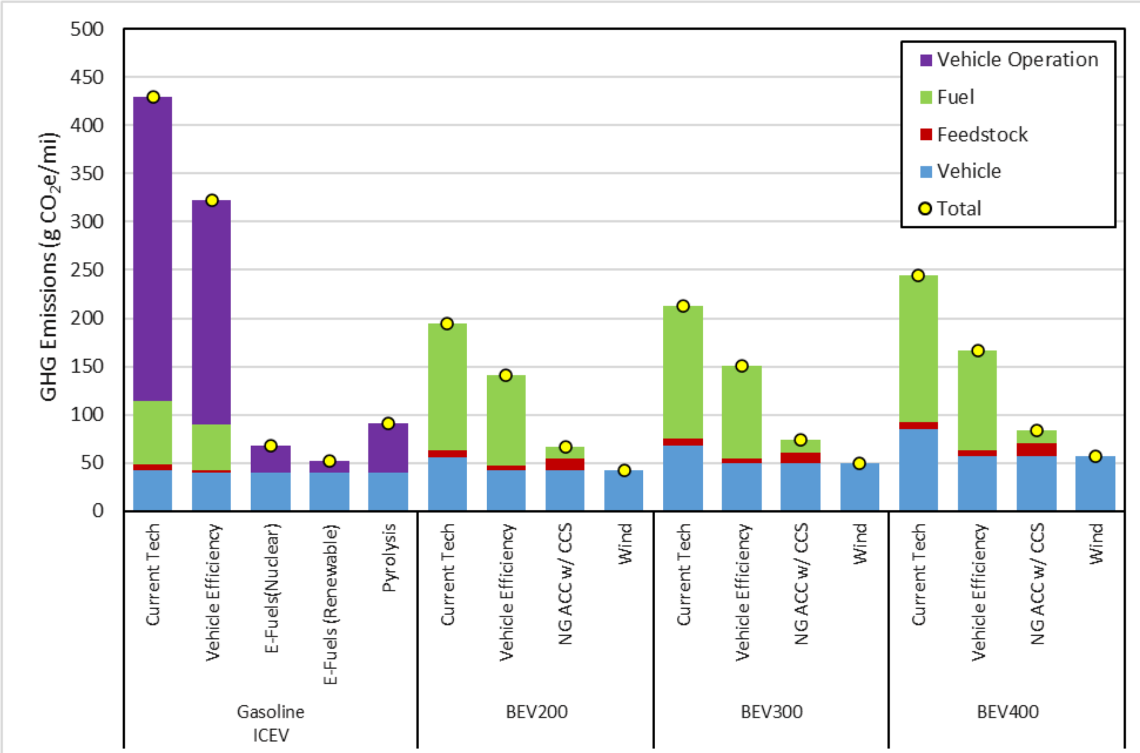

Figure B.8. Emissions for BEV200, BEV300, and BEV400 compared with small SUV gasoline ICEV CURRENT TECHNOLOGY and vehicle efficiency gains

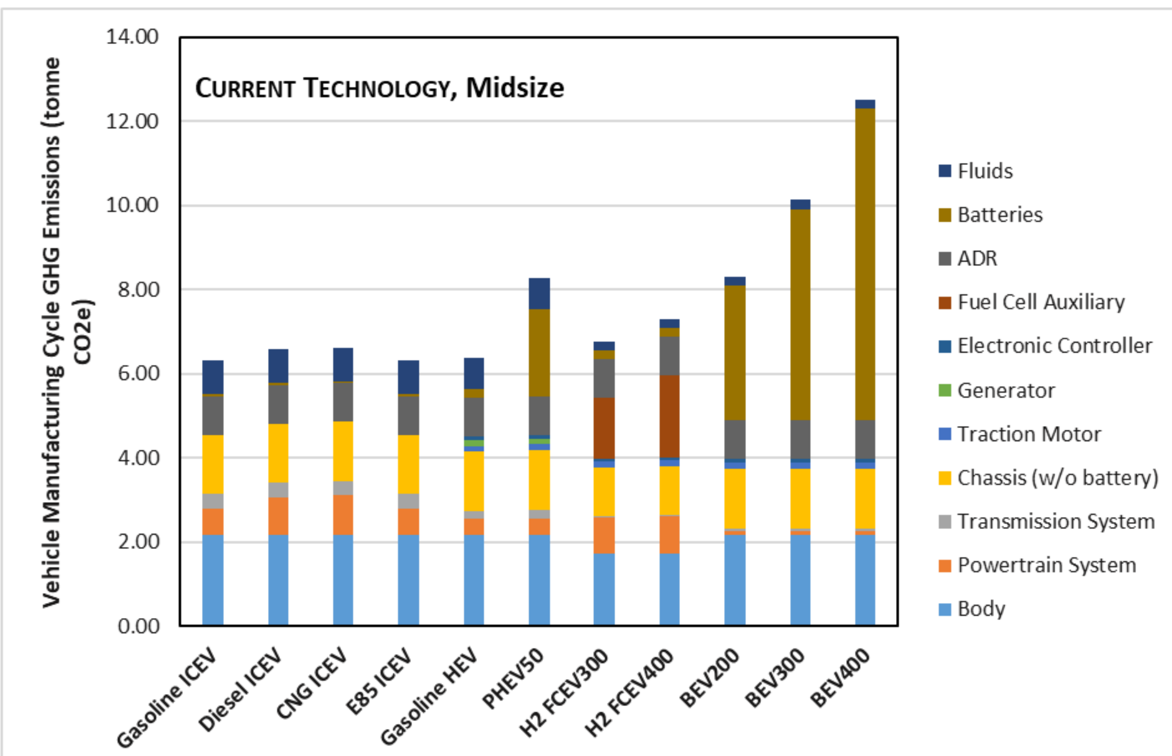

Figure B.9. Vehicle cycle GHG emissions by vehicle component for the Current Technology midsize sedan case

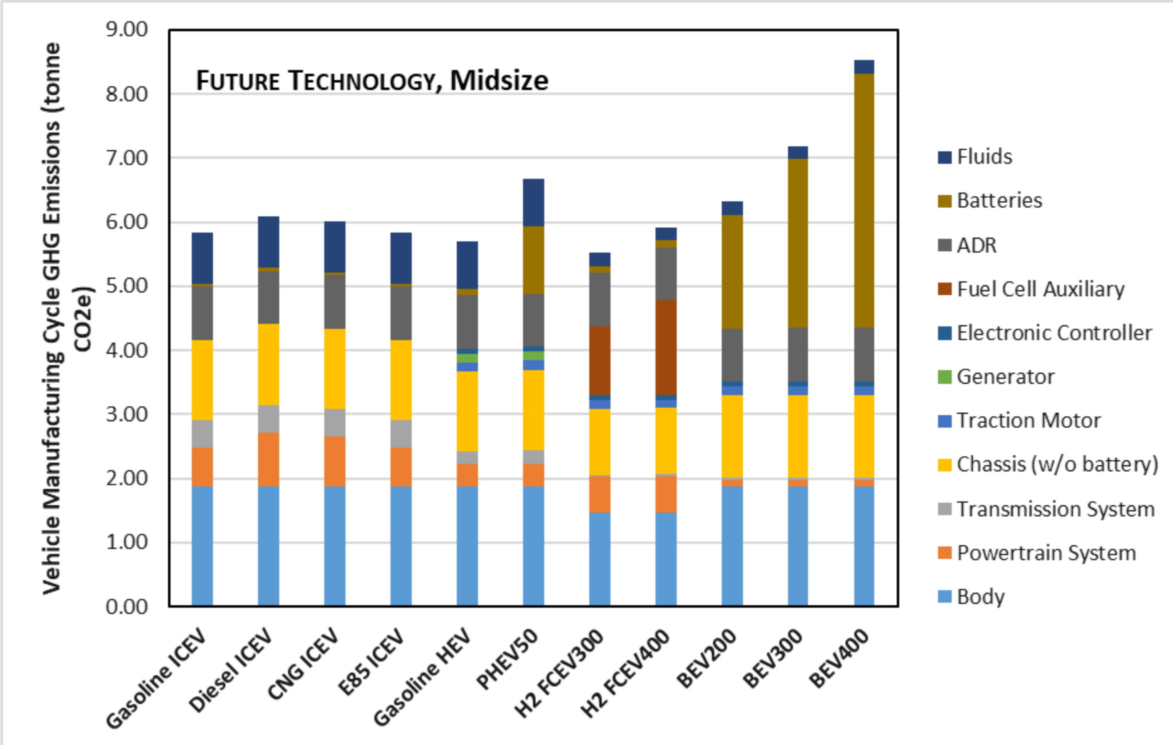

Figure B.10. Vehicle cycle GHG emissions by vehicle component for the Future Technology midsize sedan case

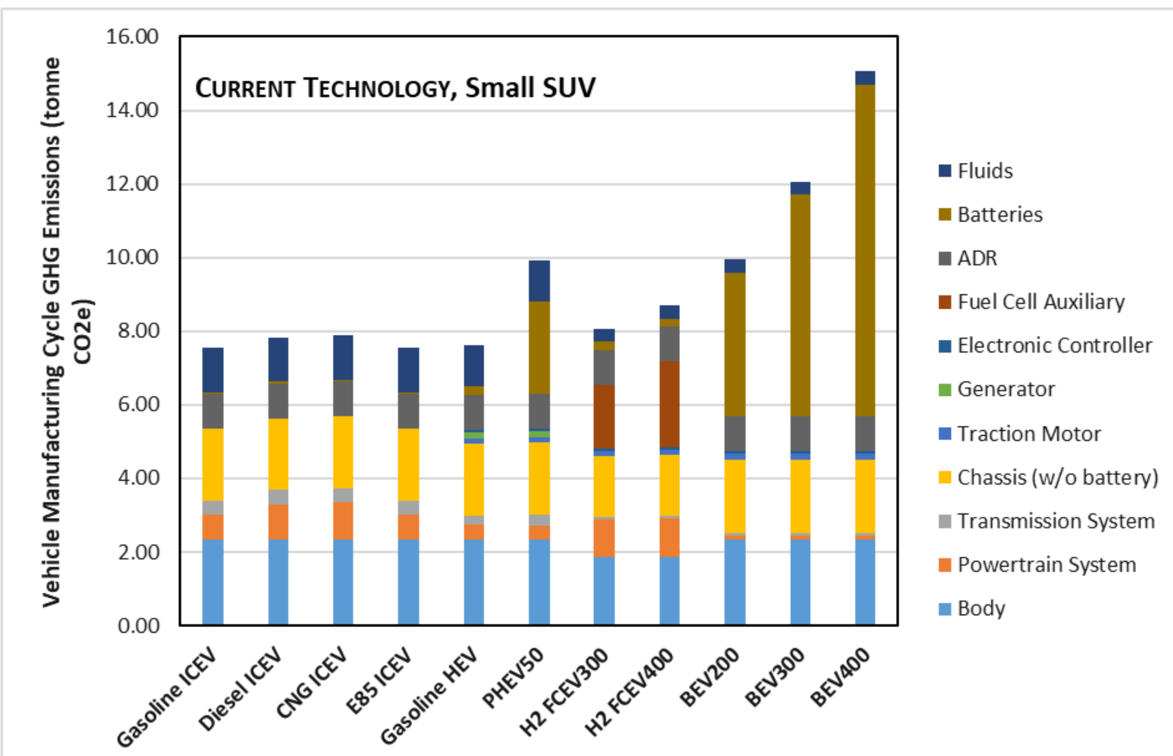

Figure B.11. Vehicle cycle GHG emissions by vehicle component for the CURRENT TECHNOLOGY small SUV case

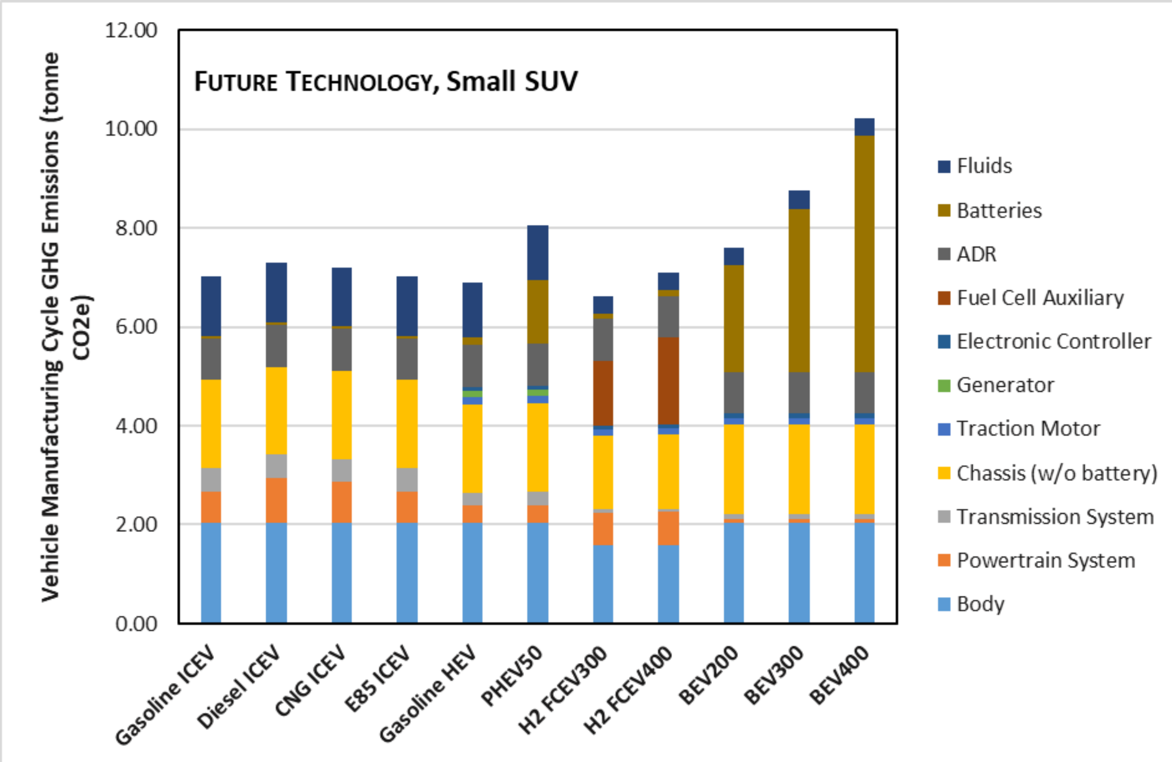

Figure B.12. Vehicle cycle GHG emissions by vehicle component for the FUTURE TECHNOLOGY small SUV case

Appendix C: SENSITIVITY STUDIES

One observation from the analysis in Section 8, is that the GHG emissions associated with vehicle production may serve as a lower bound for vehicles that are capable of achieving zero or near-zero GHG emissions in their well-to-wheels stage. Thus, it is important to acknowledge that the GREET model does not have temporal or technological variation for most material production pathways that could accommodate vast technological advancements to reduce the GHG emissions associated with material production in the FUTURE TECHNOLOGY pathways.

Therefore, a sensitivity analysis was conducted for the FUTURE TECHNOLOGY ICEV Small SUV to consider a limited set of potential conditions for GHG reductions in vehicle manufacturing. The analysis considered three scenarios for the analysis in addition to the baseline 2035 scenario. The sensitivity cases are defined as follows:

- First, steel produced with reduced GHG emissions, termed *green steel*, which utilized 100% H_2 steel, but with the baseline 2035 electrical grid. All other materials were produced with baseline conditions.
- Second, steel produced with reduced GHG emissions, i.e., green steel, which utilized 100% H_2 steel, but with all electricity used in steel being from wind-based sources. All other materials were produced with baseline conditions.
- Finally, steel produced with reduced GHG emissions which was 75% H_2 steel (as described in the second scenario), 25% recycled steel, and all electricity used in all vehicle and material production stages being from wind.

Results of this sensitivity analysis are presented in Figure C.1. Moving from left to right in that figure, we see a 12%, 24%, and 37% reduction in vehicle cycle GHG emissions from the baseline for the green steel, green steel with wind-based electricity, and system level wind-based electricity coupled with 75% green steel and 25% recycled steel, respectively. Thus, steel decarbonization can be a major source (24%) of opportunity for emissions reduction, but such a level of reduction requires a major electricity grid shift which would likely also include the transformation of other sectors along the way (i.e., if steel transformation stages are using 100% wind-based electricity, then wind electricity is likely to be more predominant on the grid at large). This highlights that while the analysis in this report may appear to suggest a lowest level of achievable GHG emissions with each vehicle-fuel pathway, that level is itself restricted by modeling assumptions. The relaxation of those assumptions presented here indicates that further GHG reduction is available within the vehicle-fuel system through decarbonization of the manufacturing sector.

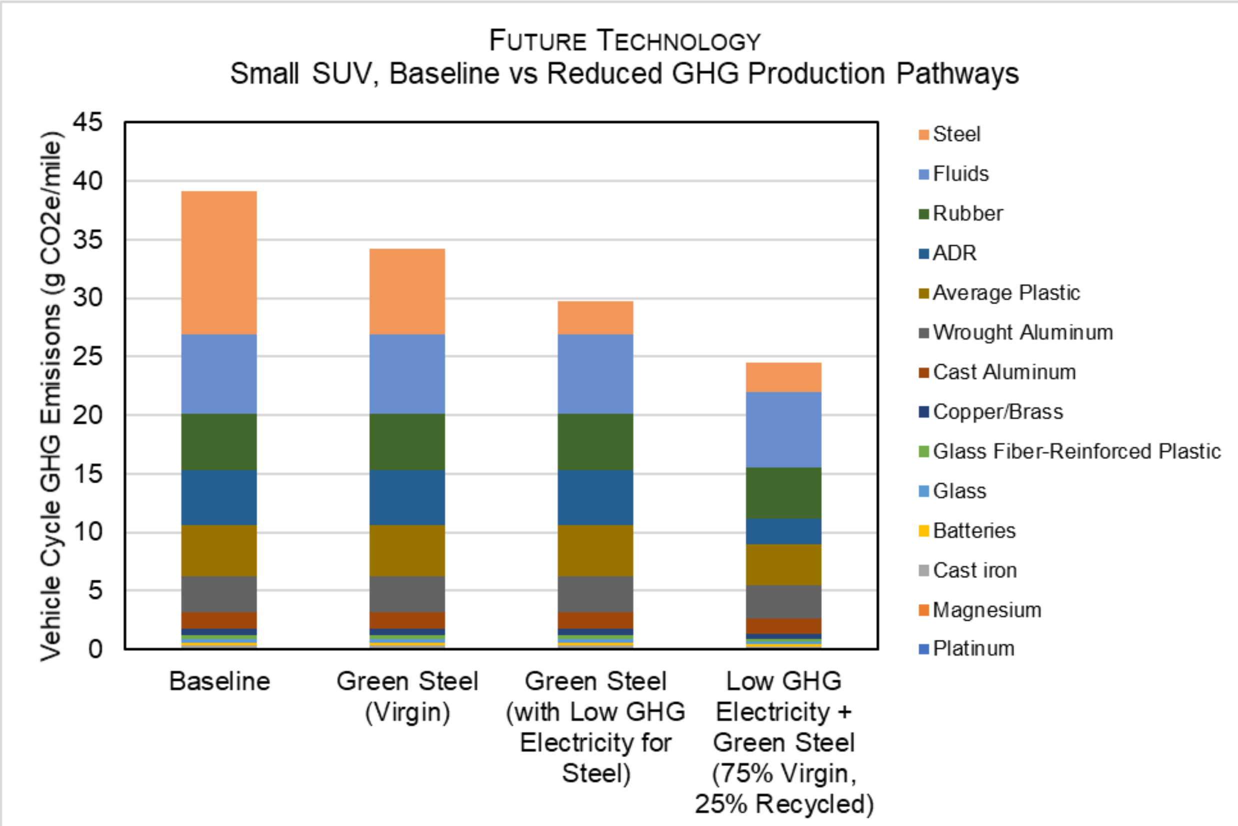

Figure C.1. Sensitivity analysis of vehicle cycle manufacturing stage

A sensitivity analysis was also conducted for the FUTURE TECHNOLOGY pathways to examine the impact of converting background electricity profiles for energy production to wind-based electricity. This serves to identify the degree to which grid decarbonization has compounding effects on energy production, including refining, processing, and distribution stages for the various fuels. Figure C.2 presents the results of this study with the solid bars indicating the baseline condition for the small SUV with high technology progression and the error bars show the sensitivity case. The results show that using this wind-based electricity for background processes has an especially pronounced effect for the FCEVs.

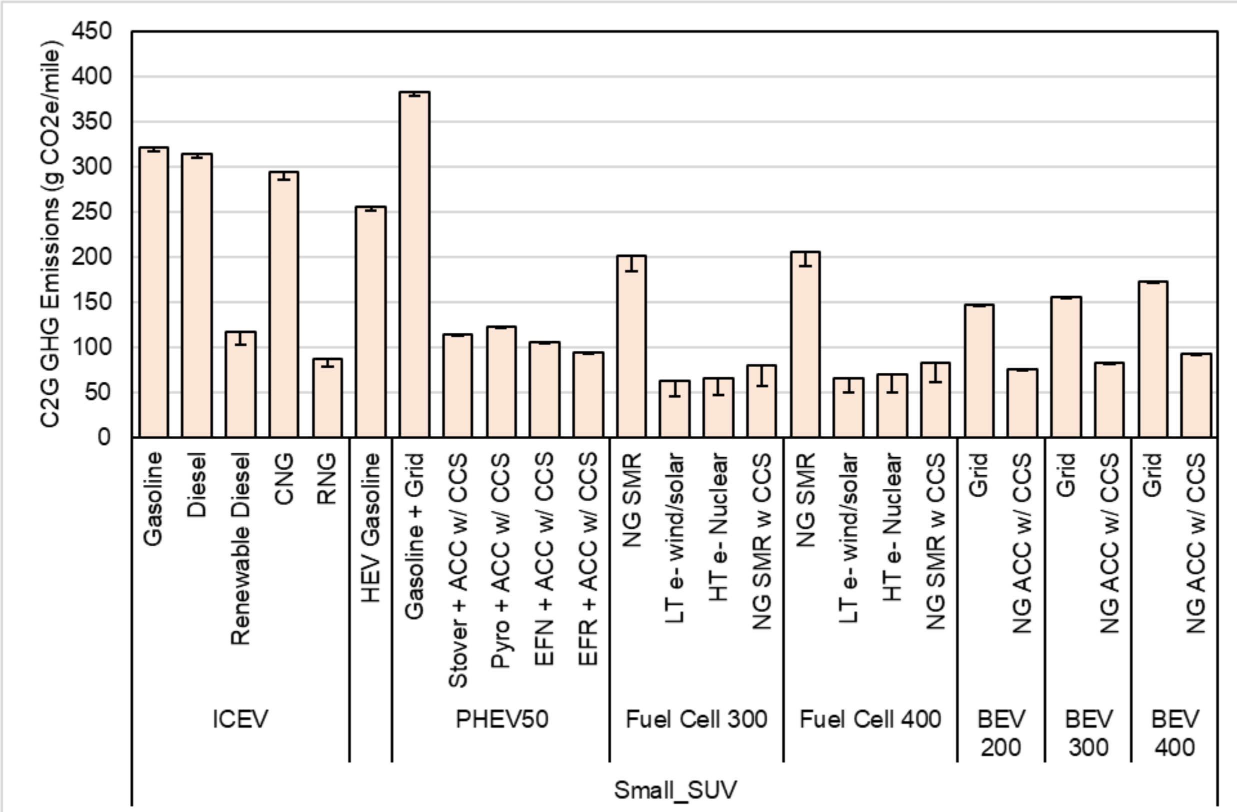

Figure C.2. Sensitivity analysis of utilizing wind electricity for background grid activities of energy production

Appendix D: DETAILS FOR LOW POWERTRAIN TECHNOLOGY STUDIES

The main text of this analysis reports and examines FUTURE TECHNOLOGY parameters and results associated with the evaluation of the high powertrain technology advancement. This appendix provides the FUTURE TECHNOLOGY parameters and results for the low powertrain technology not already available within the main text.

Table D.1. 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 (units are in the first column)

Vehicle and Test			Test Cycle		On-road Adjusted	
			CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
Midsize Sedan	Gasoline SI Turbo ICEV (mpgge)	UDDS	37.1	43.6	28.3	32.6
		HWFET	49.6	58.4	34.1	39.5
	Diesel CI ICEV (mpgge)	UDDS	42.3	50.6	31.7	37.0
		HWFET	54.6	63.4	37.2	42.3
	CNG SI ICEV (mpgge)	UDDS	33.4	42.7	25.8	32.0
		HWFET	43.9	56.2	30.6	38.2
	Gasoline SI HEV (mpgge)	UDDS	72.3	79.7	49.7	53.6
		HWFET	67.4	74.2	44.7	48.4
	H_2 FCEV300 (mpgge)	UDDS	86.5	99.9	60.6	69.9
		HWFET	106.8	121.8	74.8	85.3
	H_2 FCEV400 (mpgge)	UDDS	84.8	98.1	59.4	68.7
		HWFET	105.8	120.8	74.0	84.6
	BEV200 (Wh/mi)	UDDS	139	127	199	181
		HWFET	171	157	245	225
	BEV300 (Wh/mi)	UDDS	145	130	207	186
		HWFET	181	164	258	234
	BEV400 (Wh/mi)	UDDS	169	149	241	212
		HWFET	193	173	276	247
Small SUV	Gasoline SI Turbo ICEV (mpgge)	UDDS	33.7	39.1	26.0	29.6
		HWFET	42.8	50.1	29.9	34.4
	Diesel CI ICEV (mpgge)	UDDS	38.7	45.8	29.3	34.0
		HWFET	47.7	54.4	33.0	37.0
	CNG SI ICEV (mpgge)	UDDS	30.4	38.6	23.7	29.3
		HWFET	38.6	49.0	27.2	33.8
	Gasoline SI HEV (mpgge)	UDDS	61.5	67.6	43.6	47.1
		HWFET	56.6	61.9	38.4	41.5
	H_2 FCEV300 (mpgge)	UDDS	72.8	84.0	50.9	58.8
		HWFET	85.9	97.4	60.1	68.2
	H_2 FCEV400 (mpgge)	UDDS	71.3	82.3	49.9	57.6
		HWFET	85.1	96.7	59.6	67.7
	BEV200 (Wh/mi)	UDDS	166	151	237	216
		HWFET	214	198	306	283
	BEV300 (Wh/mi)	UDDS	173	156	247	222
		HWFET	225	205	321	293
	BEV400 (Wh/mi)	UDDS	202	178	288	255
		HWFET	240	215	342	308

Table D.2. Autonomie-modeled test cycle and on-road adjusted fuel economy and electricity consumption for the gasoline PHEV50

Vehicle and Test		Mode and Units	Test Cycle		On-road Adjusted	
			CURRENT TECH	FUTURE TECH	CURRENT TECH	FUTURE TECH
Midsize PHEV50 (EREV)	UDDS	CD electric (Wh/mi)	177	162	253	232
		CS engine (mpgge)	70	80	49	56
	HWFET	CD electric (Wh/mi)	205	189	293	270
		CS engine (mpgge)	64	71	45	50
Small SUV PHEV50 (EREV)	UDDS	CD electric (Wh/mi)	206	189	295	270
		CS engine (mpgge)	59	68	42	47
	HWFET	CD electric (Wh/mi)	252	234	360	334
		CS engine (mpgge)	52	58	36	40

Table D.3. 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
Midsize Sedans	Gasoline SI Turbo ICEV (mpgge)	31	35	100	117
	Diesel CI ICEV (mpgge)	34	39	110	117
	CNG SI ICEV (mpgge)	28	35	90	104
	E85 SI ICEV (mpgge) [b]	31	35	100	117
	Gasoline SI HEV (mpgge)	46	49	149	158
	H_2 FCEV300 (mpgge)	67	76	217	227
	H_2 FCEV400 (mpgge)	66	75	213	224
	BEV200 (mpgge)	124	141	405	419
	BEV300 (mpgge)	118	136	385	408
	BEV400 (mpgge)	107	125	349	376
	PHEV50 (EREV)				
	CD electricity consumption (Wh/mi)	276	254		
	CD fuel consumption (Btu/mi)	2	2		
	CD distance (mi)	50	50		
	CS fuel economy (mpgge)	45.6	51.3	149	170
	CD fuel economy (mpgge)	119.1	129.2	388	383
Small SUVs	Gasoline SI Turbo ICEV (mpgge)	27	32	100	118
	Diesel CI ICEV (mpgge)	31	35	111	124
	CNG SI ICEV (mpgge)	25	31	91	105
	E85 SI ICEV (mpgge) [b]	27	32	100	118
	Gasoline SI HEV (mpgge)	40	43	144	155
	H_2 FCEV300 (mpgge)	55	62	199	210
	H_2 FCEV400 (mpgge)	54	62	196	207
	BEV200 (mpgge)	101	114	368	383
	BEV300 (mpgge)	97	110	351	372
	BEV400 (mpgge)	88	102	319	347
	PHEV50 (EREV)				
	CD electricity consumption (Wh/mi)	332	306		
	CD fuel consumption (Btu/mi)	2	2		
	CD distance (mi)	50	50		
	CS fuel economy (mpgge)	37.9	42.2	138	159
	CD fuel economy (mpgge)	98.8	107.1	360	358

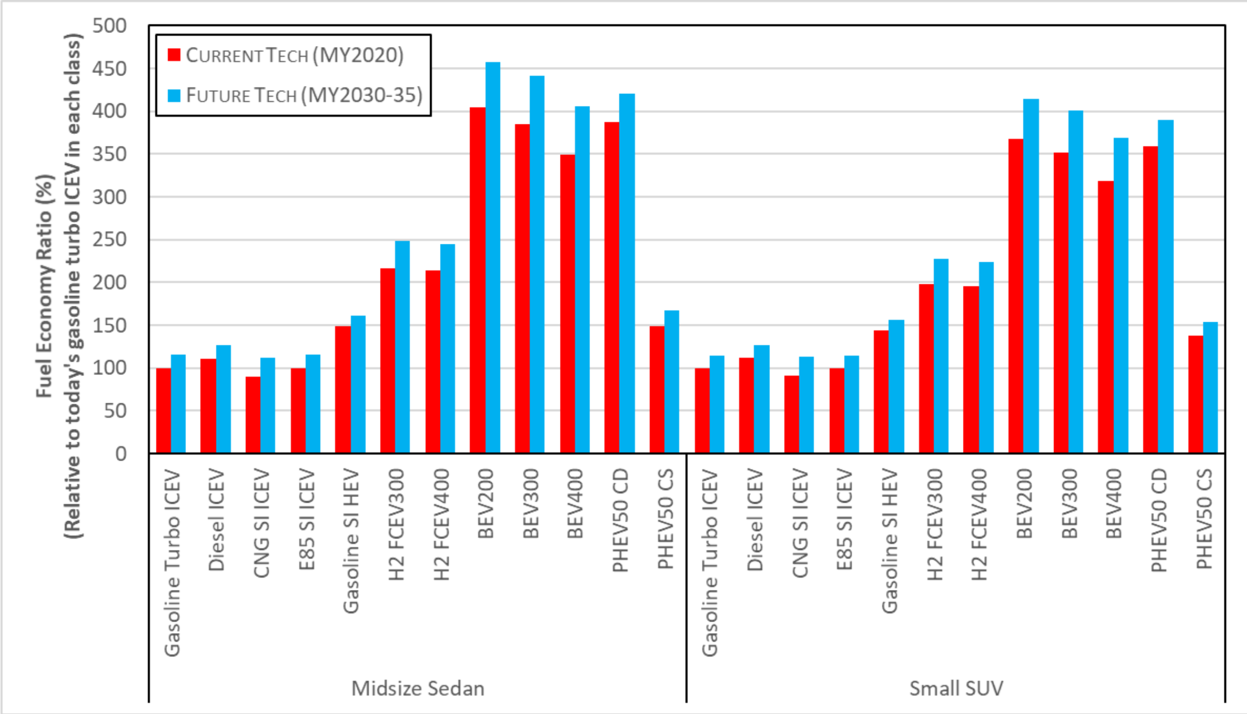

Figure D.1. Vehicle fuel economy (mpgge) relative to a CURRENT TECHNOLOGY gasoline turbo ICEV (per class) assuming low powertrain technological progress

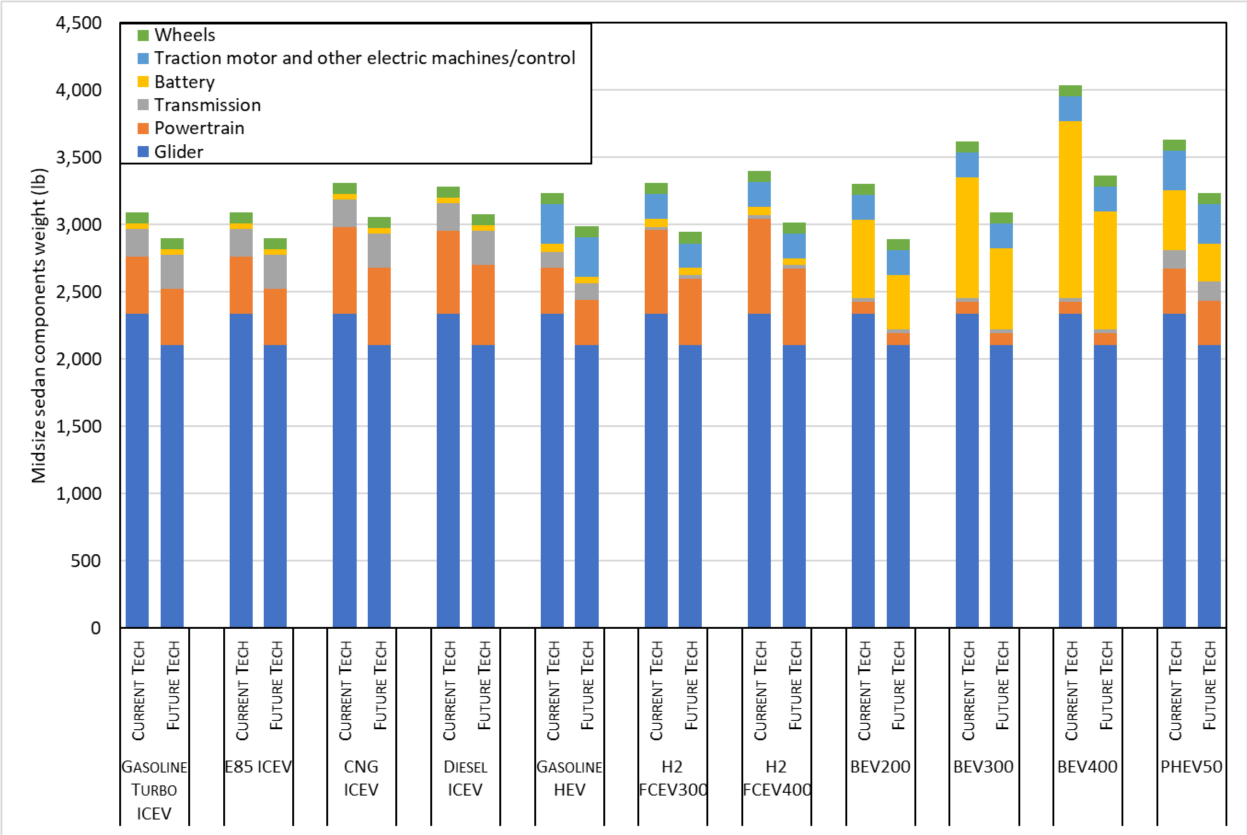

Figure D.2. Midsize sedan component weight results (lb)

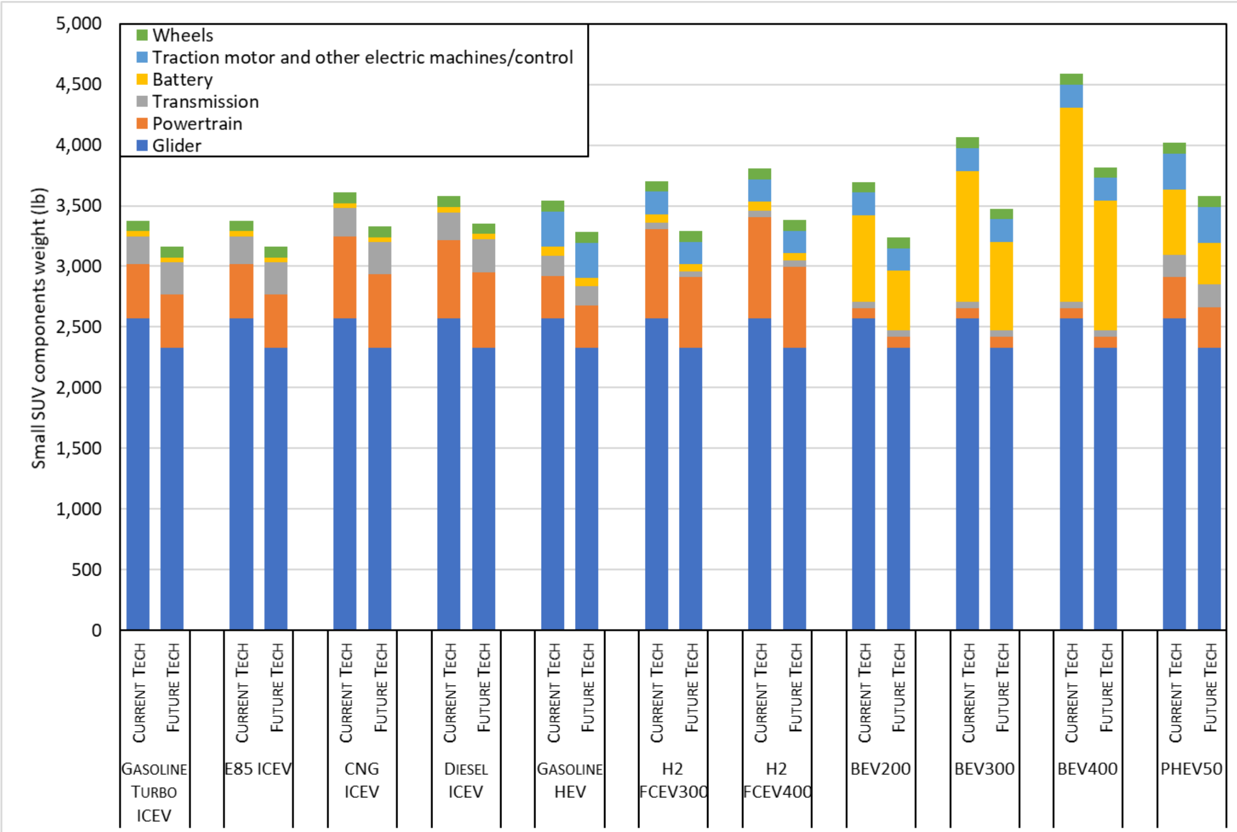

Figure D.3. Small SUV component weight results (lb)

Table D.4. Sedan weight and composition results

CURRENT TECHNOLOGY	Gasoline Turbo ICEV	E85 ICEV	CNG ICEV	Diesel ICEV	Gasoline HEV	H_2 FCEV300	H_2 FCEV400	BEV200	BEV300	BEV400	PHEV50
Vehicle weight (lb)	3,093	3,093	3,310	3,285	3,234	3,313	3,402	3,303	3,620	4,039	3,635
Weight composition											
Glider	75.6%	75.6%	70.6%	71.1%	72.3%	70.5%	68.7%	70.8%	64.6%	57.9%	64.3%
Powertrain	13.8%	13.8%	19.5%	18.7%	10.6%	18.7%	20.8%	2.7%	2.4%	2.2%	9.2%
Transmission	6.6%	6.6%	6.2%	6.2%	3.7%	0.8%	0.8%	0.8%	0.7%	0.7%	3.9%
Battery	1.3%	1.3%	1.2%	1.3%	2.0%	1.9%	1.8%	17.7%	24.8%	32.6%	12.2%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	8.9%	5.5%	5.4%	5.5%	5.1%	4.6%	8.1%
Wheels	2.7%	2.7%	2.5%	2.6%	2.6%	2.5%	2.5%	2.5%	2.3%	2.1%	2.3%
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV300**	**H_2 FCEV400**	**BEV200**	**BEV300**	**BEV400**	**PHEV50**
Vehicle weight	2,899	2,899	3,057	3,079	2,987	2,944	3,017	2,894	3,090	3,366	3,238
Weight composition											
Glider	72.7%	72.7%	68.9%	68.4%	70.5%	71.6%	69.8%	72.8%	68.2%	62.6%	65.1%
Powertrain	14.3%	14.3%	18.7%	19.2%	11.2%	16.7%	18.7%	3.0%	2.9%	2.6%	10.1%
Transmission system	8.7%	8.7%	8.3%	8.2%	4.0%	0.9%	0.9%	0.9%	0.9%	0.8%	4.4%
Battery	1.4%	1.4%	1.3%	1.4%	1.8%	1.7%	1.7%	14.0%	19.5%	26.0%	8.9%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	9.7%	6.2%	6.1%	6.3%	5.9%	5.5%	9.1%
Wheels	2.9%	2.9%	2.7%	2.7%	2.8%	2.8%	2.8%	2.9%	2.7%	2.5%	2.6%

Table D.5. Small SUV weight and composition results

CURRENT TECHNOLOGY	Gasoline Turbo ICEV	E85 ICEV	CNG ICEV	Diesel ICEV	Gasoline HEV	H_2 FCEV300	H_2 FCEV400	BEV200	BEV300	BEV400	PHEV50
Vehicle weight (lb)	3,377	3,377	3,608	3,576	3,541	3,703	3,807	3,697	4,065	4,588	4,017
Weight composition											
Glider	76.0%	76.0%	71.2%	71.8%	72.5%	69.4%	67.5%	69.5%	63.2%	56.0%	63.9%
Powertrain	13.3%	13.3%	18.9%	18.0%	10.0%	19.9%	22.0%	2.4%	2.2%	1.9%	8.6%
Transmission	6.9%	6.9%	6.4%	6.5%	4.6%	1.4%	1.4%	1.4%	1.3%	1.2%	4.6%
Battery	1.2%	1.2%	1.1%	1.2%	2.2%	1.9%	1.9%	19.3%	26.5%	34.8%	13.3%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	8.2%	5.1%	4.9%	5.1%	4.7%	4.2%	7.4%
Wheels	2.6%	2.6%	2.4%	2.5%	2.5%	2.4%	2.3%	2.4%	2.2%	1.9%	2.2%
FUTURE TECHNOLOGY	**Gasoline ICEV**	**E85 ICEV**	**CNG ICEV**	**Diesel ICEV**	**Gasoline HEV**	**H_2 FCEV300**	**H_2 FCEV400**	**BEV200**	**BEV300**	**BEV400**	**PHEV50**
Vehicle weight	3,162	3,162	3,329	3,354	3,281	3,292	3,383	3,239	3,475	3,817	3,579
Weight composition											
Glider	73.6%	73.6%	69.9%	69.4%	71.0%	70.7%	68.8%	71.9%	67.0%	61.0%	65.1%
Powertrain	13.8%	13.8%	18.1%	18.6%	10.5%	17.6%	19.8%	2.7%	2.5%	2.3%	9.4%
Transmission system	8.5%	8.5%	8.1%	8.0%	5.0%	1.6%	1.6%	1.6%	1.5%	1.4%	5.2%
Battery	1.3%	1.3%	1.2%	1.3%	1.9%	1.7%	1.8%	15.3%	21.1%	28.1%	9.7%
Traction motor and other electric machines/control	0.0%	0.0%	0.0%	0.0%	8.9%	5.6%	5.5%	5.7%	5.3%	4.9%	8.3%
Wheels	2.8%	2.8%	2.6%	2.6%	2.7%	2.7%	2.6%	2.7%	2.5%	2.3%	2.5%

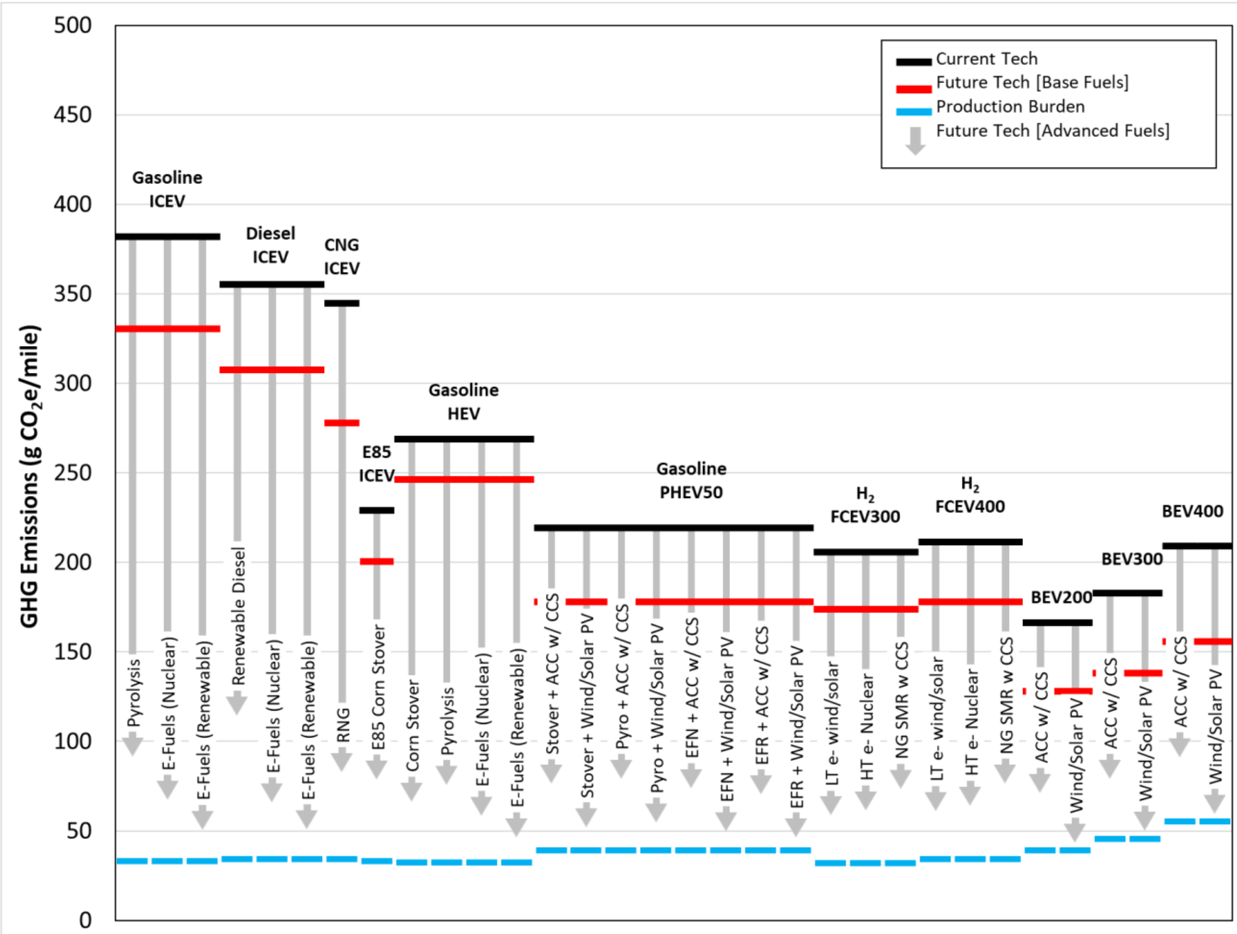

Figure D.4. GHG emissions for midsize sedans, assuming low technological progress. Numerical values are given in Table 44.

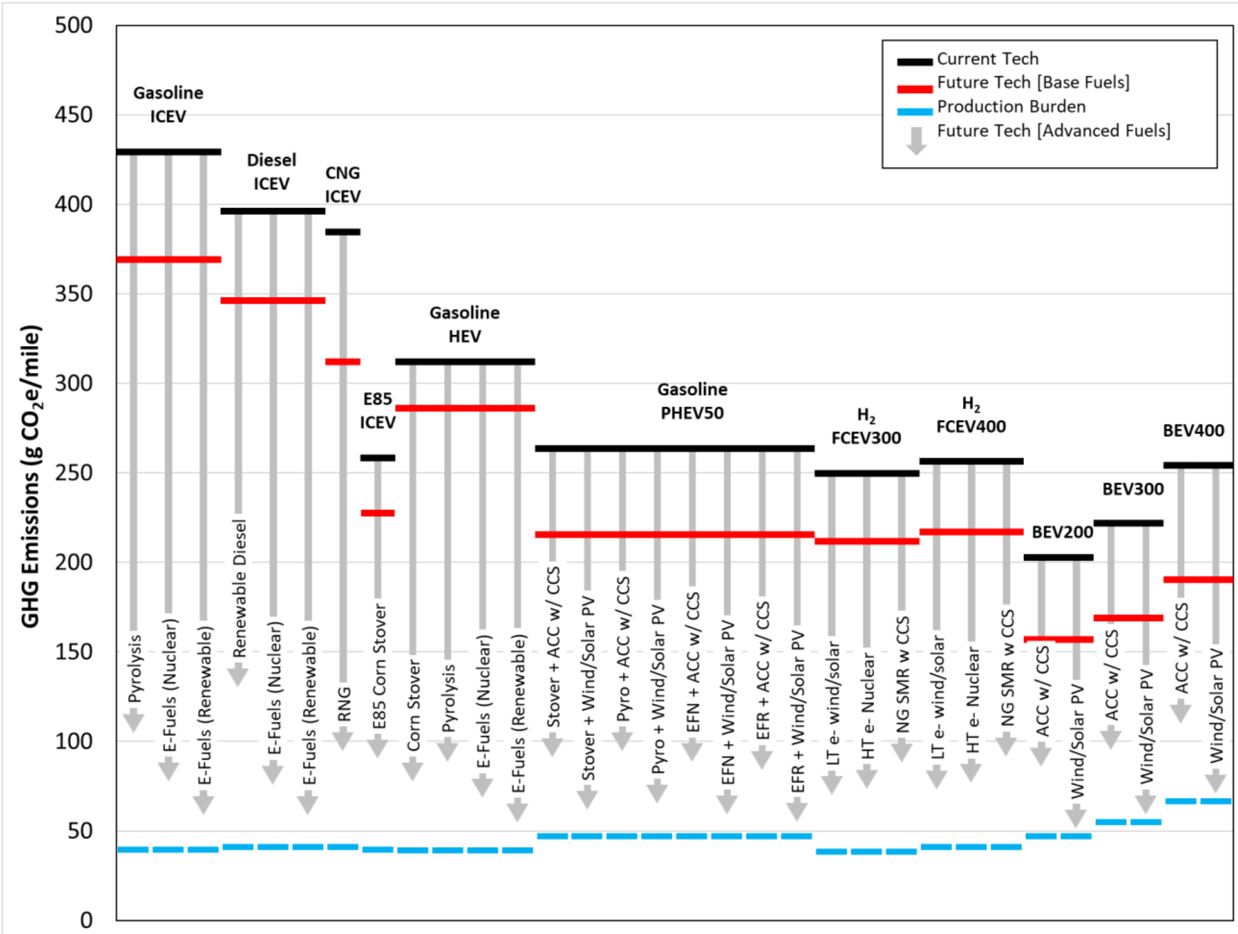

Figure D.5. GHG emissions for small SUVs, assuming low technological progress. Numerical values are given in Table 45.

Table D.6. GHG emissions for Future Technology case for mid-sized sedans shown in Figure D.4 (g CO_2e/mile)

Pathway	Gasoline Turbo ICEV	Diesel ICEV	CNG ICEV	E85 ICEV	Gasoline HEV	Gasoline PHEV50	H_2 FCEV 300	H_2 FCEV 400	BEV200	BEV300	BEV400
Current Technology	382	355	345	229	269	219	206	211	166	182	209
Vehicle efficiency gain	331	308	278	200	246	178	174	178	128	138	156
Forest residue pyrolysis	87	128	–	–	71	–	–	–	–	–	–
Soybean	–	110	–	–	–	–	–	–	–	–	–
E-fuels (nuclear)	63	61	–	–	54	–	–				
E-fuels (renewable)	46	46	–	–	42	–	–				
RNG	–	–	78	–	–	–	–	–	–	–	–
Corn stover	–	–	–	74	62	–	–	–	–	–	–
Solar/wind electricity	–	–	–	–	–	–	54	57	39	45	55
Nuclear electrolysis	–	–	–	–	–	–	57	59	–	–	–
NG SMR with CCS	–	–	–	–	–	–	69	72	–	–	–
Stover + ACC w/ CCS	–	–	–	–	–	72	–	–	–	–	–
Stover + wind/solar	–	–	–	–	–	47	–	–	–	–	–
Pyrolysis + ACC w/ CCS	–	–	–	–	–	74	–	–	–	–	–
Pyrolysis + wind/solar	–	–	–	–	–	50	–	–	–	–	–
E-fuel (nuclear) + ACC w/ CCS	–	–	–	–	–	69	–	–	–	–	–
E-fuel (nuclear) + wind/solar	–	–	–	–	–	45	–	–	–	–	–
E-fuel (renewable) + ACC w/ CCS	–	–	–	–	–	66	–	–	–	–	–
E-fuel (renewable) + wind/solar	–	–	–	–	–	42	–	–	–	–	–

Table D.7. GHG emissions for the FUTURE TECHNOLOGY case for small SUVs shown in Figure D.5 (g CO_2e/mile)

Pathway	Gasoline Turbo ICEV	Diesel ICEV	CNG ICEV	E85 ICEV	Gasoline HEV	Gasoline PHEV50	H_2 FCEV 300	H_2 FCEV 400	BEV200	BEV300	BEV400
Current Technology	429	396	384	258	312	264	250	256	203	221	254
Vehicle efficiency gain	374	346	312	227	286	215	212	217	157	169	190
Forest residue pyrolysis	100	128	–	–	84	–	–	–	–	–	–
Soybean	–	125	–	–	–	–	–	–	–	–	–
E-fuels (Nuclear)	73	71	–	–	64	–	–				
E-fuels (Renewable)	54	54	–	–	50	–	–				
RNG	–	–	90	–	–	–	–	–	–	–	–
Corn stover	–	–	–	86	73	–	–	–	–	–	–
Solar/wind electricity	–	–	–	–	–	–	65	68	47	55	66
Nuclear electrolysis	–	–	–	–	–	–	69	72	–	–	–
NG SMR with CCS	–	–	–	–	–	–	83	87	–	–	–
Stover + ACC w/ CCS	–	–	–	–	–	86	–	–	–	–	–
Stover + wind/solar	–	–	–	–	–	57	–	–	–	–	–
Pyrolysis + ACC w/ CCS	–	–	–	–	–	90	–	–	–	–	–
Pyrolysis + wind/solar	–	–	–	–	–	61	–	–	–	–	–
E-fuel (nuclear) + ACC w/ CCS	–	–	–	–	–	84	–	–	–	–	–
E-fuel (nuclear) + wind/solar	–	–	–	–	–	54	–	–	–	–	–
E-fuel (renewable) + ACC w/ CCS	–	–	–	–	–	79	–	–	–	–	–
E-fuel (renewable) + wind/solar	–	–	–	–	–	50	–	–	–	–	–

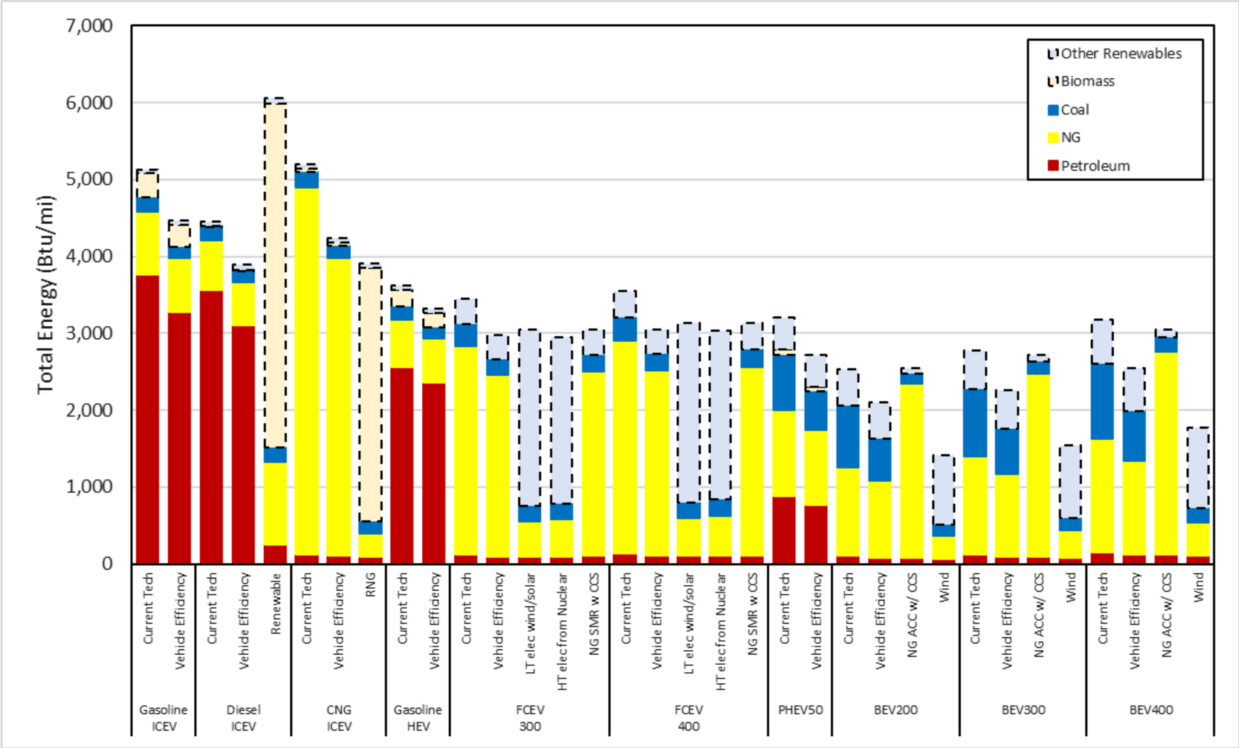

Figure D.6. GREET results of energy consumption for all midsize vehicle-fuel combinations (Btu/mi). Each bar is segmented by energy source.

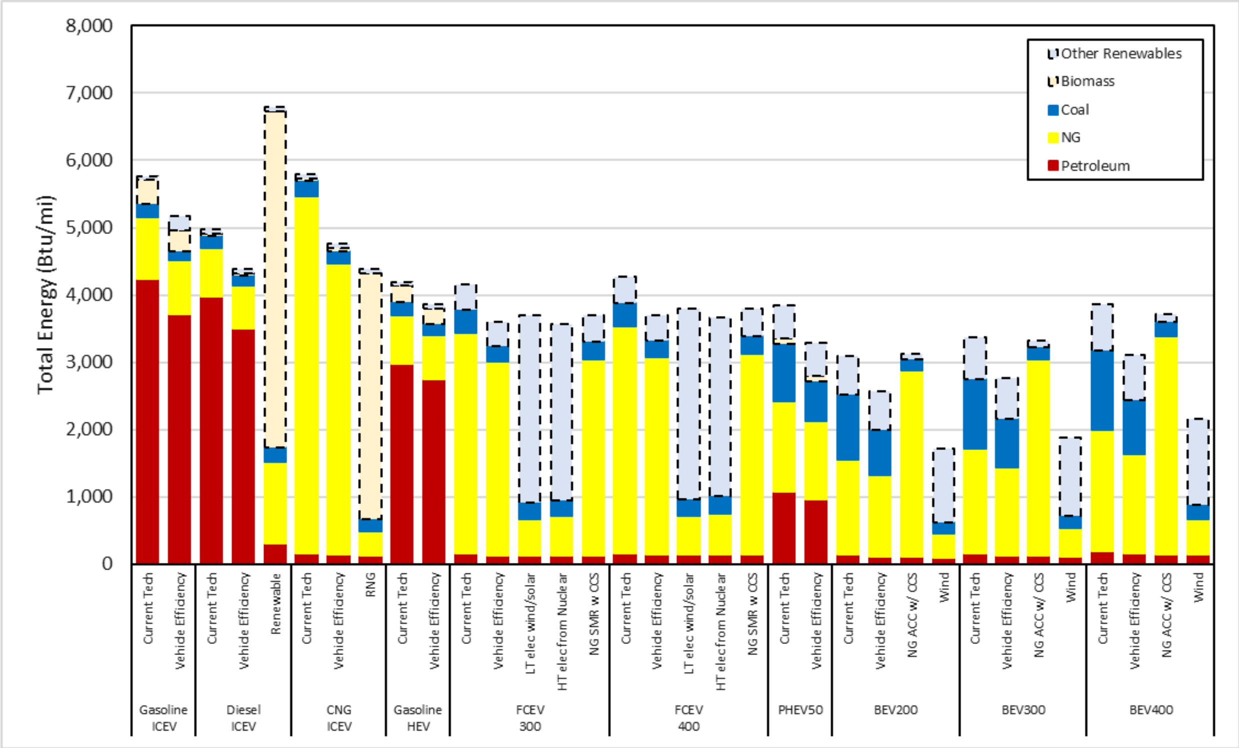

Figure D.7. GREET results of energy consumption for all small SUV vehicle-fuel combinations (Btu/mi). Each bar is segmented by energy source.

Table D.8. Total midsize sedan energy consumed, as shown in Figure D.6 (Btu/mi)

Vehicle		Total	Petroleum	NG	Coal	Biomass	Other/Renewables
Gasoline ICEV	Current Tech	5,133	3,770	806	186	316	54
	Vehicle Efficiency	4,466	3,275	705	151	277	58
	Pyrolysis	9,283	(112)	1,516	(187)	8,066	-
	E-fuels (Nuclear)	5,831	17	51	22	-	5,743
	E-Fuels (Renewable)	7,804	8	5	3	-	7,789
Diesel ICEV	Current Tech	4,456	3,564	642	172	20	58
	Vehicle Efficiency	3,891	3,104	565	141	19	61
	Renewable	6,054	254	1,076	190	4,473	61
	E-fuels (Nuclear)	5,258	15	46	19	-	5,179
	E-Fuels (Renewable)	7,037	7	5	2	-	7,024
CNG ICEV	Current Tech	5,203	118	4,775	209	44	58
	Vehicle Efficiency	4,241	110	3,869	161	40	61
	RNG	3,907	96	303	158	3,288	61
E85	Current Tech	6,865	234	447	96	6,089	-
	Vehicle Efficiency	5,950	203	387	83	5,278	-
	Corn Stover	9,789	308	224	(91)	9,348	-
Gasoline HEV	Current Tech	3,616	2,555	620	175	212	53
	Vehicle Efficiency	3,324	2,362	566	143	198	55
FCEV 300	Current Tech	3,446	120	2,708	286	-	331
	Vehicle Efficiency	2,977	102	2,361	197	-	317
	LT Elec. Wind/Solar	3,055	95	461	196	-	2,303
	HT Elec. Nuclear	2,952	100	485	205	-	2,162
	NG SMR w/ CCS	3,054	103	2,396	218	-	337
FCEV 400	Current Tech	3,545	133	2,771	299	-	341
	Vehicle Efficiency	3,056	113	2,412	205	-	325
	LT Elec. Wind/Solar	3,135	106	487	204	-	2,338
	HT Elec. Nuclear	3,030	111	511	213	-	2,196
	NG SMR w/ CCS	3,134	114	2,447	226	-	346
PHEV50	Current Tech	3,200	879	1,122	724	64	410
	Vehicle Efficiency	2,725	774	972	505	58	416
BEV200	Current Tech	2,531	106	1,155	802	-	468
	Vehicle Efficiency	2,105	86	993	553	-	473
	NG ACC w/ CCS	2,548	79	2,262	137	-	71
	Wind	1,416	72	301	135	-	909
BEV300	Current Tech	2,777	128	1,278	865	-	506
	Vehicle Efficiency	2,263	102	1,073	588	-	500
	NG ACC w/ CCS	2,722	95	2,388	156	-	84
	Wind	1,549	87	356	154	-	952
BEV400	Current Tech	3,179	157	1,473	976	-	573
	Vehicle Efficiency	2,545	126	1,213	652	-	554
	NG ACC w/ CCS	3,045	117	2,643	182	-	101
	Wind	1,768	109	432	181	-	1,046

Table D.9. Total small SUV energy consumed as shown in Figure D.7 (Btu/mi)

Vehicle		Total	Petroleum	NG	Coal	Biomass	Other Renewables
Gasoline ICEV	Current Tech	5,767	4,234	915	206	353	59
	Vehicle Efficiency	5,051	3,705	806	167	311	62
	Pyrolysis	10,304	(124)	1,683	(208)	8,954	-
	E-fuels (Nuclear)	6,523	19	57	24	-	6,424
	E-Fuels (Renewable)	8,729	9	6	3	-	8,712
Diesel ICEV	Current Tech	4,969	3,968	727	189	22	62
	Vehicle Efficiency	4,382	3,493	647	155	22	66
	Renewable	6,798	308	1,216	210	4,998	66
	E-fuels (Nuclear)	5,841	17	51	22	-	5,753
	E-Fuels (Renewable)	7,817	8	5	3	-	7,802
CNG ICEV	Current Tech	5,800	157	5,302	230	48	63
	Vehicle Efficiency	4,754	147	4,319	178	45	65
	RNG	4,382	132	353	174	3,657	65
E85	Current Tech	7,620	259	496	106	6,759	-
	Vehicle Efficiency	6,656	227	433	93	5,904	-
	Corn Stover	10,950	344	251	(102)	10,456	-
Gasoline HEV	Current Tech	4,190	2,970	721	197	245	58
	Vehicle Efficiency	3,860	2,750	660	161	229	60
FCEV 300	Current Tech	4,161	150	3,286	339	-	385
	Vehicle Efficiency	3,604	129	2,872	233	-	370
	LT Elec. Wind/Solar	3,700	121	553	232	-	2,794
	HT Elec. Nuclear	3,573	126	582	243	-	2,623
	NG SMR w/ CCS	3,698	130	2,915	259	-	394
FCEV 400	Current Tech	4,278	166	3,361	354	-	396
	Vehicle Efficiency	3,702	143	2,936	243	-	381
	LT Elec. Wind/Solar	3,799	134	584	242	-	2,839
	HT Elec. Nuclear	3,671	140	613	253	-	2,665
	NG SMR w/ CCS	3,797	144	2,979	269	-	406
PHEV50	Current Tech	3,841	1,072	1,344	860	77	488
	Vehicle Efficiency	3,286	954	1,167	599	70	495
BEV200	Current Tech	3,084	136	1,407	973	-	569
	Vehicle Efficiency	2,572	112	1,213	672	-	576
	NG ACC w/ CCS	3,119	102	2,778	158	-	81
	Wind	1,723	94	360	156	-	1,114
BEV300	Current Tech	3,365	161	1,548	1,045	-	612
	Vehicle Efficiency	2,759	131	1,308	712	-	608
	NG ACC w/ CCS	3,323	122	2,925	181	-	96
	Wind	1,881	112	426	179	-	1,164
BEV400	Current Tech	3,858	198	1,788	1,180	-	693
	Vehicle Efficiency	3,102	160	1,478	790	-	674
	NG ACC w/ CCS	3,715	150	3,234	214	-	118
	Wind	2,150	140	521	212	-	1,277

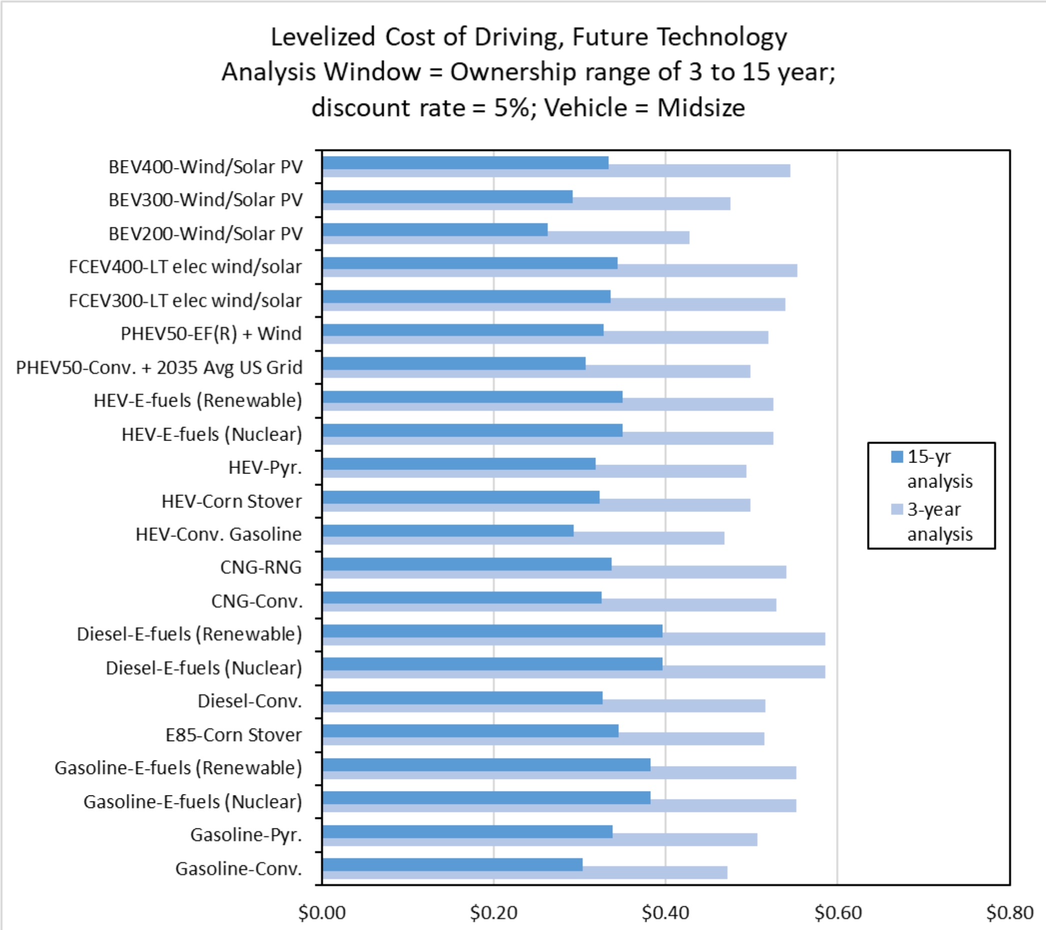

Figure D.8. 3-year and 15-year LCD results by vehicle-fuel pathway for the Future Technology midsize sedan case

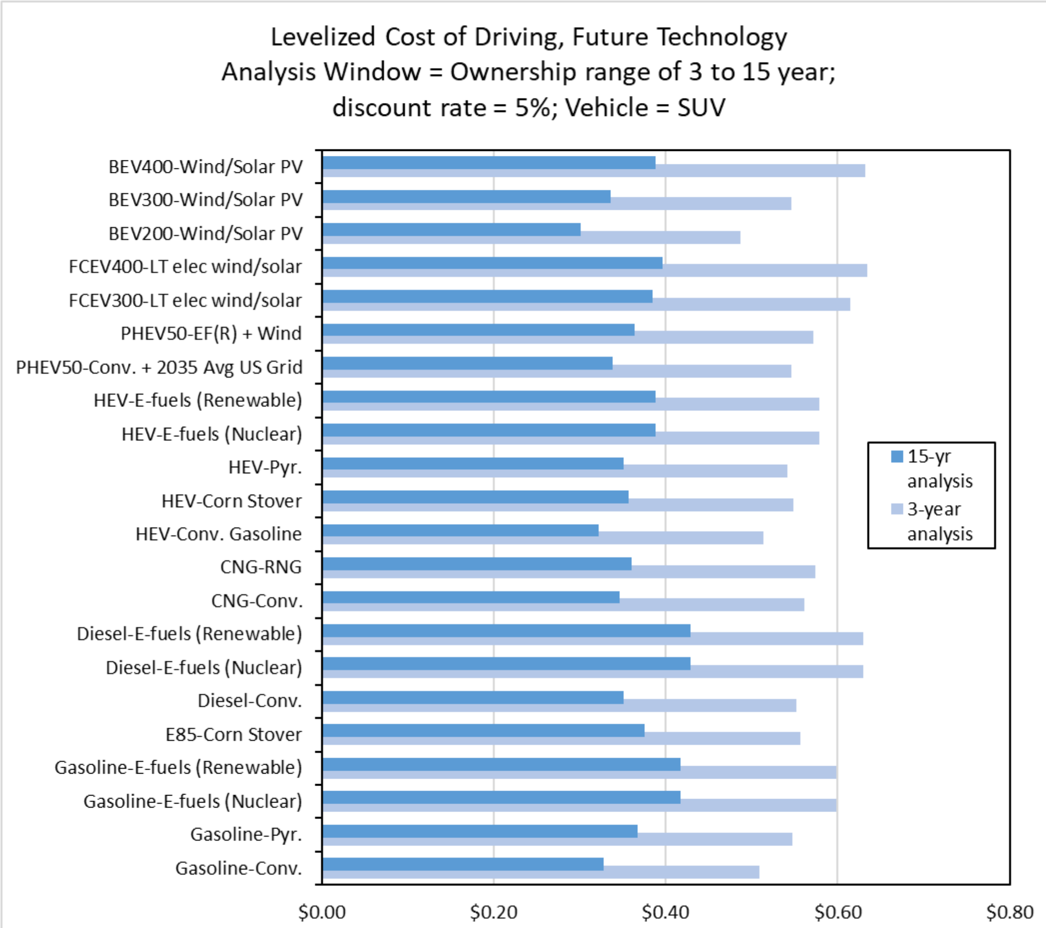

Figure D.9. 3-year and 15-year LCD results by vehicle-fuel pathway for FUTURE TECHNOLOGY small SUV case

Table D.10. Costs and GHG emissions for the FUTURE TECHNOLOGY midsize sedan case

Base Case (5% discount rate, mid-point fuel cost)		**Vehicle Cost (2020$)**	**Fuel Cost ($/gge)**	**Vehicle F/E (mpgge)**	**GHG Emissions (g CO_2e/mi)**	**3-year Cost ($/mi)**	**15-year Cost ($/mi)**
Vehicle	**Fuel**						
Gasoline	Conv.	29,920	2.37	35.4	331	0.47	0.30
Gasoline	Pyr.	29,920	3.60	35.4	110	0.51	0.34
Gasoline	E-fuels (nuclear)	29,920	5.19	35.4	64	0.55	0.38
Gasoline	E-fuels (renewable)	29,920	5.19	35.4	47	0.55	0.38
E85	Corn Stover	29,920	3.87	35.4	130	0.51	0.35
Diesel	Conv.	33,426	2.47	39.0	309	0.52	0.33
Diesel	E-fuels (nuclear)	33,426	5.19	39.0	62	0.59	0.40
Diesel	E-fuels (renewable)	33,426	5.19	39.0	47	0.59	0.40
CNG	Conv.	35,931	1.44	34.5	279	0.53	0.33
CNG	RNG	35,931	1.85	34.5	79	0.54	0.34
HEV	Conv. Gasoline	31,062	2.37	49.5	247	0.47	0.29
HEV	Corn Stover	31,062	3.87	49.5	103	0.50	0.32
HEV	Pyr.	31,062	3.60	49.5	88	0.49	0.32
HEV	E-fuels (nuclear)	31,062	5.19	49.5	55	0.53	0.35
HEV	E-fuels (renewable)	31,062	5.19	49.5	43	0.53	0.35
PHEV50	Pyr. + NG ACC	33,921	3.6/3.51	51.3/114.	152	0.51	0.31
PHEV50	Pyr. + NG ACC w/ CCS	33,921	3.6/4.04	51.3/114.	80	0.51	0.31
PHEV50	Pyr. + Wind	33,921	3.6/4.76	51.3/114.	56	0.51	0.32
PHEV50	Pyr. + Solar PV	33,921	3.6/4.76	51.3/114.	56	0.51	0.32
FCEV300	LT Elec. Wind/Solar	35,912	4.00	76.3	55	0.54	0.34
FCEV300	NG SMR w/ CCS	35,912	4.00	76.3	70	0.54	0.34
FCEV400	LT Elec. Wind/Solar	36,895	4.00	75.3	57	0.55	0.34
FCEV400	NG SMR w/ CCS	36,895	4.00	75.3	73	0.55	0.34
BEV200	2035 Avg U.S. Grid	29,064	4.10	140.5	129	0.42	0.26
BEV200	Wind	29,064	4.76	140.5	40	0.43	0.26
BEV300	2035 Avg U.S. Grid	32,556	4.10	135.6	139	0.47	0.29
BEV300	Wind	32,556	4.76	135.6	47	0.48	0.29
BEV400	2035 Avg U.S. Grid	37,432	4.10	124.6	157	0.54	0.33
BEV400	Wind	37,432	4.76	124.6	56	0.55	0.33

Table D.11. Costs and GHG emissions for the FUTURE TECHNOLOGY small SUV case

Base Case (5% discount rate, mid-point fuel cost)		**Vehicle Cost (2020$)**	**Fuel Cost ($/gge)**	**Vehicle F/E (mpgge)**	**GHG Emissions (g CO_2e/mi)**	**3-year Cost ($/mi)**	**15-year Cost ($/mi)**
Vehicle	**Fuel**						
Gasoline	Conv.	32,015	2.37	31.5	375	0.51	0.33
Gasoline	Pyr.	32,015	3.60	31.5	126	0.55	0.37
Gasoline	E-fuels (nuclear)	32,015	5.19	31.5	74	0.60	0.42
Gasoline	E-fuels (renewable)	32,015	5.19	31.5	55	0.60	0.42
E85	Corn Stover	32,015	3.87	31.5	149	0.56	0.38
Diesel	Conv.	35,519	2.47	34.9	348	0.55	0.35
Diesel	E-fuels (nuclear)	35,519	5.19	34.9	72	0.63	0.43
Diesel	E-fuels (renewable)	35,519	5.19	34.9	55	0.63	0.43
CNG	Conv.	38,026	1.44	31.0	313	0.56	0.35
CNG	RNG	38,026	1.85	31.0	91	0.57	0.36
HEV	Conv. Gasoline	33,815	2.37	42.8	287	0.51	0.32
HEV	Corn Stover	33,815	3.87	42.8	120	0.55	0.36
HEV	Pyr.	33,815	3.60	42.8	104	0.54	0.35
HEV	E-fuels (nuclear)	33,815	5.19	42.8	65	0.58	0.39
HEV	E-fuels (renewable)	33,815	5.19	42.8	51	0.58	0.39
PHEV50	Pyr. + NG ACC	36,868	3.6/3.51	42.2/94.5	184	0.55	0.35
PHEV50	Pyr. + NG ACC w/ CCS	36,868	3.6/4.04	42.2/94.5	97	0.55	0.35
PHEV50	Pyr. + Wind	36,868	3.6/4.76	42.2/94.5	68	0.56	0.35
PHEV50	Pyr. + Solar PV	36,868	3.6/4.76	42.2/94.5	68	0.56	0.35
FCEV300	LT Elec. Wind/Solar	40,656	4.00	62.5	66	0.61	0.39
FCEV300	NG SMR w/ CCS	40,656	4.00	62.5	85	0.61	0.39
FCEV400	LT Elec. Wind/Solar	42,022	4.00	61.6	70	0.63	0.40
FCEV400	NG SMR w/ CCS	42,022	4.00	61.6	88	0.63	0.40
BEV200	2035 Avg U.S. Grid	32,898	4.10	113.9	158	0.48	0.30
BEV200	Wind	32,898	4.76	113.9	48	0.49	0.30
BEV300	2035 Avg U.S. Grid	37,116	4.10	110.2	170	0.54	0.33
BEV300	Wind	37,116	4.76	110.2	56	0.55	0.34
BEV400	2035 Avg U.S. Grid	43,195	4.10	101.6	192	0.63	0.38
BEV400	Wind	43,195	4.76	101.6	68	0.63	0.39

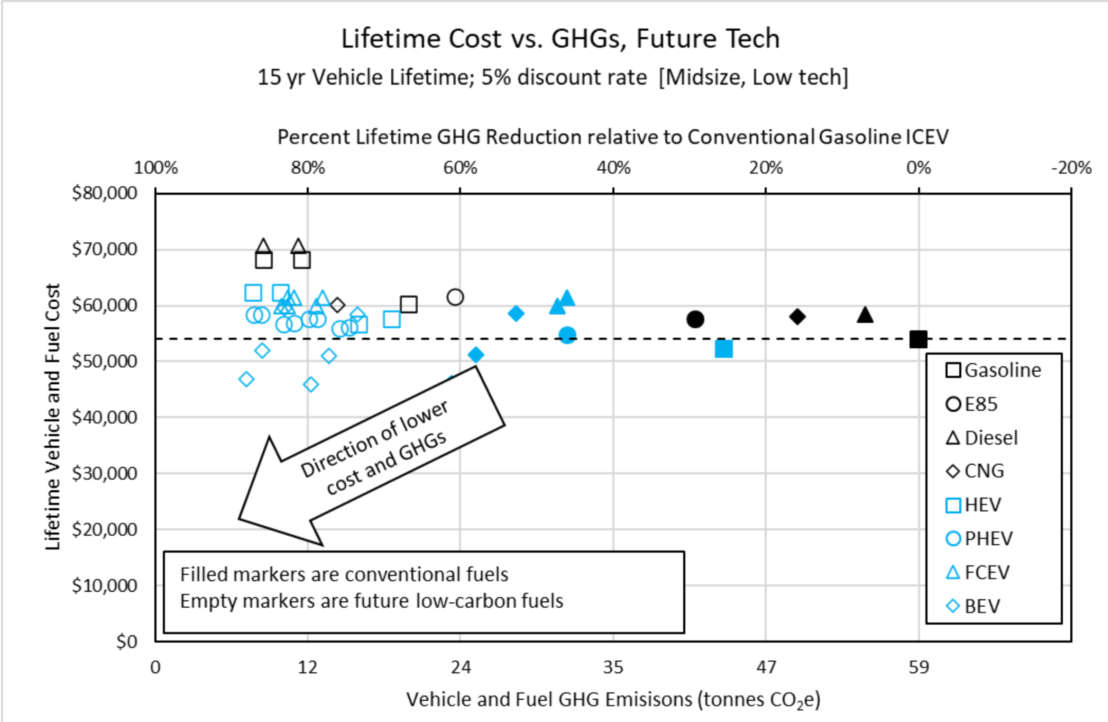

Figure D.10. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY midsize sedan case over its lifetime assuming low technology progress.

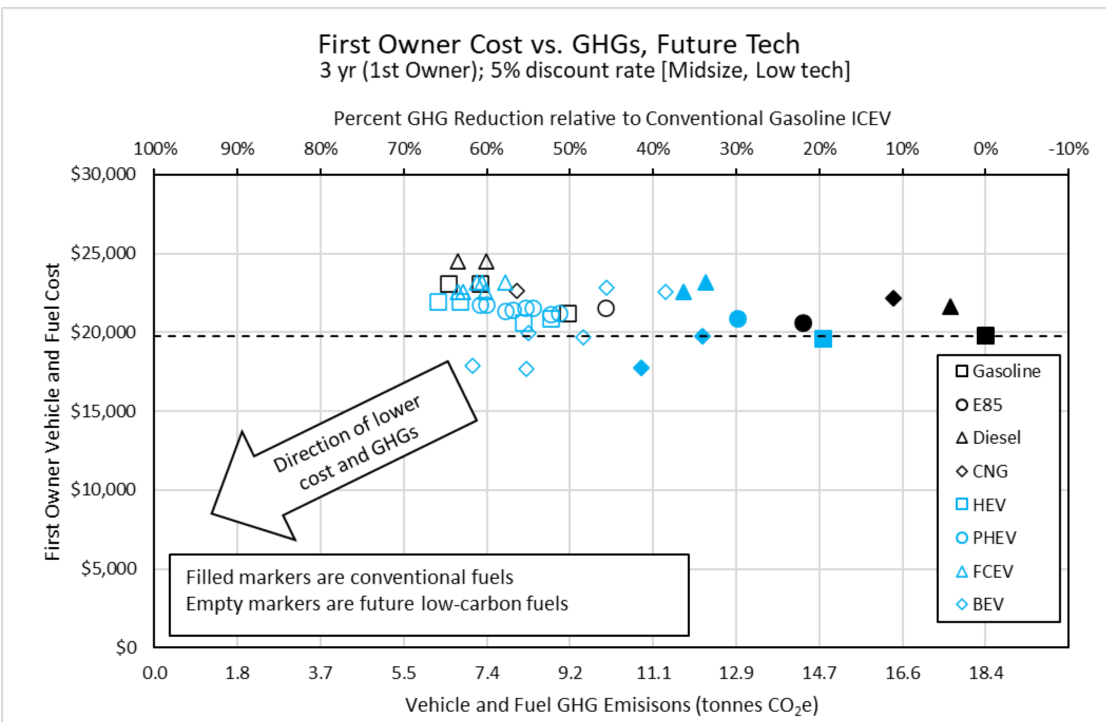

Figure D.11. First owner COSTS versus GHG emissions by vehicle-fuel pathway for the FUTURE TECHNOLOGY midsize sedan case for the first owner assuming low technology progress.

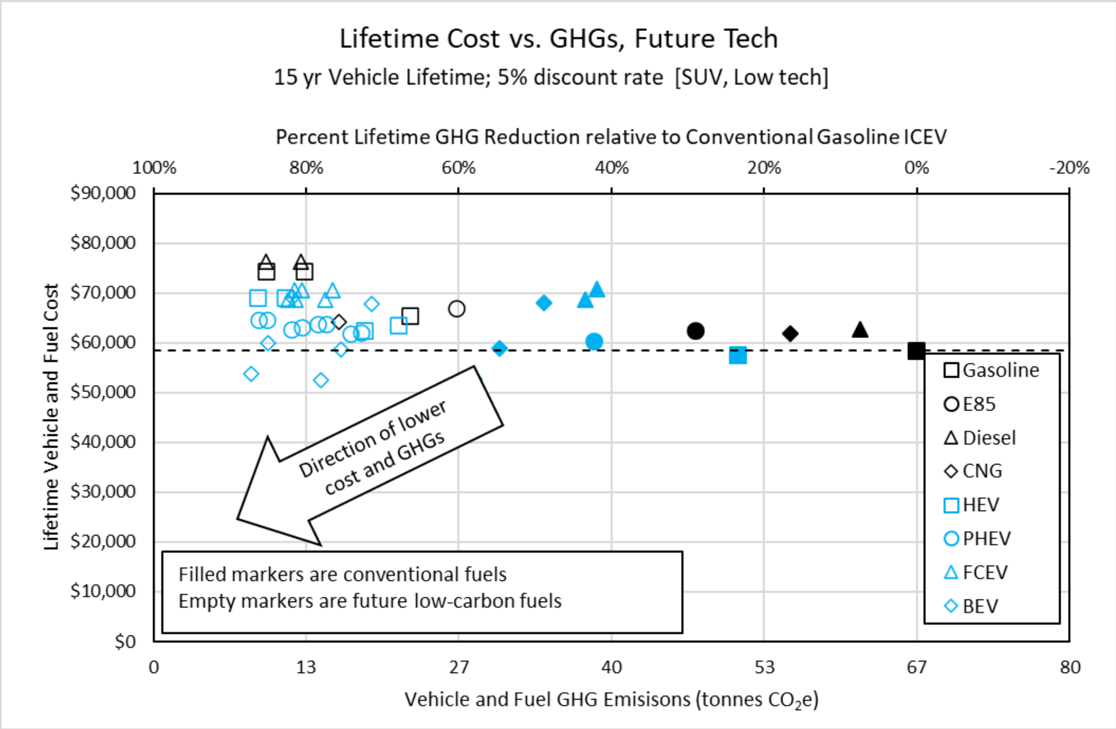

Figure D.12. Lifetime costs versus GHG emissions by vehicle-fuel pathway for the Future Technology small SUV case over its lifetime assuming low technology progress.

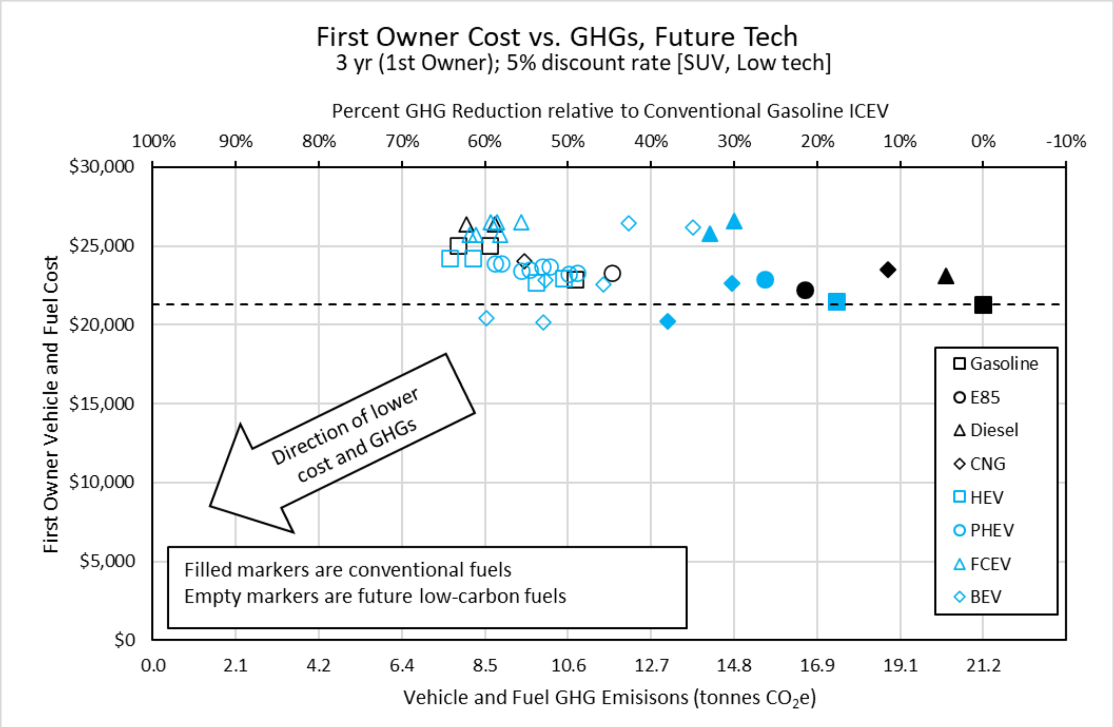

Figure D.13. First owner costs versus GHG emissions by vehicle-fuel pathway for the Future Technology small SUV case for the first owner assuming low technology progress.

Table D.12. Cost of avoided GHG emissions for CURRENT TECHNOLOGY and FUTURE TECHNOLOGY midsize sedan cases, relative to their respective gasoline ICEVs

Cost of Avoided GHG Emissions Summary, Base Case (5% discount rate, mid-point 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 Case				
E85 - Corn	19.8	120	4.7	120
Diesel - Conventional	4.7	1,110	0.9	2,560
CNG - CNG	6.7	1,480	1.3	2,970
HEV - Conventional Gasoline	20.2	140	4.7	350
PHEV50 - Conventional Gasoline	28.9	400	5.2	980
FCEV300 - NG SMR	31.4	1,250	7.0	2,020
FCEV400 - NG SMR	30.4	1,370	6.4	2,370
BEV200 - 2020 Avg U.S. Grid Mix	38.4	150	7.5	390
BEV300 - 2020 Avg U.S. Grid Mix	35.4	450	5.3	1,330
BEV400 - 2020 Avg U.S. Grid Mix	30.6	970	2.3	5,420
FUTURE TECHNOLOGY Case				
Gasoline - Pyr.	39.5	160	9.3	160
Gasoline - E-fuels (nuclear)	47.7	300	11.2	300
Gasoline - E-fuels (renewable)	50.7	280	11.9	280
E85 - Corn Stover	35.9	210	8.4	210
Diesel - Conv.	4.1	1,050	0.8	2,420
Diesel - E-fuels (nuclear)	47.9	350	11.1	430
Diesel - E-fuels (renewable)	50.6	330	11.7	410
CNG - Conv.	9.3	430	2.0	1,170
CNG - RNG	44.9	140	10.4	280
HEV - Conv. Gasoline	15.1	-120	3.6	-40
HEV - Corn Stover	40.8	90	9.6	120
HEV - Pyr.	43.3	60	10.2	90
HEV - E-fuels (nuclear)	49.3	170	11.7	190
HEV - E-fuels (renewable)	51.4	160	12.2	180
PHEV50 - Pyr. + NG ACC	31.9	60	6.6	210
PHEV50 - Pyr. + NG ACC w/ CCS	44.8	40	9.6	140
PHEV50 - Pyr. + Wind	49.1	60	10.7	150
PHEV50 - Pyr. + Solar PV	49.1	60	10.7	150
FCEV300 - LT Elec. Wind/Solar	49.3	120	11.7	240
FCEV300 - NG SMR w/ CCS	46.6	130	11.1	250
FCEV400 - LT Elec. Wind/Solar	48.8	150	11.3	300
FCEV400 - NG SMR w/ CCS	46.1	160	10.6	320
BEV200 - 2035 Avg U.S. Grid	36.0	-220	7.6	-270
BEV200 - Wind	52.0	-140	11.4	-160
BEV300 - 2035 Avg U.S. Grid	34.2	-80	6.3	-10
BEV300 - Wind	50.7	-40	10.1	20
BEV400 - 2035 Avg U.S. Grid	31.0	150	4.2	680
BEV400 - Wind	49.0	110	8.4	360

Table D.13. Cost of avoided GHG emissions for CURRENT TECHNOLOGY and FUTURE TECHNOLOGY small SUV cases, relative to their respective gasoline ICEVs

Cost of Avoided GHG Emissions Summary, Base Case (5% discount rate, mid-point 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 Case				
E85 - Corn	22.1	120	5.2	120
Diesel - Conventional	5.9	860	1.2	1,940
CNG - CNG	8.0	1,410	1.6	2,780
HEV - Conventional Gasoline	20.9	190	4.9	450
PHEV50 - Conventional Gasoline	29.4	490	5.1	1,240
FCEV300 - NG SMR	32.0	1,580	7.1	2,570
FCEV400 - NG SMR	30.8	1,740	6.3	3,060
BEV200 - 2020 Avg U.S. Grid Mix	40.3	260	7.6	640
BEV300 - 2020 Avg U.S. Grid Mix	36.9	610	5.1	1,880
BEV400 - 2020 Avg U.S. Grid Mix	31.0	1,280	1.4	11,960
FUTURE TECHNOLOGY Case				
Gasoline - Pyr.	44.4	160	10.4	160
Gasoline - E-fuels (nuclear)	53.6	300	12.6	300
Gasoline - E-fuels (renewable)	57.0	280	13.4	280
E85 - Corn Stover	40.3	210	9.5	210
Diesel - Conv.	4.9	840	0.9	1,910
Diesel - E-fuels (nuclear)	53.9	330	12.5	410
Diesel - E-fuels (renewable)	57.0	320	13.2	380
CNG - Conv.	11.0	300	2.4	920
CNG - RNG	50.6	110	11.7	240
HEV - Conv. Gasoline	15.7	-60	3.7	50
HEV - Corn Stover	45.4	120	10.7	160
HEV - Pyr.	48.4	90	11.4	120
HEV - E-fuels (nuclear)	55.3	190	13.0	230
HEV - E-fuels (renewable)	57.7	190	13.6	220
PHEV50 - Pyr. + NG ACC	34.0	100	6.9	280
PHEV50 - Pyr. + NG ACC w/ CCS	49.6	70	10.6	180
PHEV50 - Pyr. + Wind	54.8	80	11.8	180
PHEV50 - Pyr. + Solar PV	54.8	80	11.8	180
FCEV300 - LT Elec. Wind/Solar	55.0	190	13.1	340
FCEV300 - NG SMR w/ CCS	51.8	200	12.3	360
FCEV400 - LT Elec. Wind/Solar	54.4	230	12.6	420
FCEV400 - NG SMR w/ CCS	51.1	240	11.8	450
BEV200 - 2035 Avg U.S. Grid	38.6	-150	8.0	-140
BEV200 - Wind	58.3	-80	12.7	-70
BEV300 - 2035 Avg U.S. Grid	36.5	10	6.4	200
BEV300 - Wind	56.8	30	11.2	140
BEV400 - 2035 Avg U.S. Grid	32.6	290	3.9	1,270
BEV400 - Wind	54.7	200	9.0	570

Appendix E: LCD CALCULATION DETAILS AND EXAMPLES

This appendix provides more detail on the LCD calculations described in Section 9.1. 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 (2020$) not nominal dollars, and thus any assumed future inflation rate has been factored out of the analysis. Fuel costs are discussed in Section 5 and are assumed to remain constant in real dollar terms from the time of vehicle purchase through the end of the analysis period. As fuel costs are assumed to remain constant in real dollar terms, the fuel cost component of LCD can be calculated directly as the fuel cost (in 2020$/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:

$$Vehicle\ Cost\ (net) = \sum_{i=1}^{t} \frac{LCD_{veh} * VMT_i}{(1+D)^i} \qquad (4)$$

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 case gasoline ICEV pathway and for a 15-year analysis of the FUTURE TECHNOLOGY case gasoline ICEV pathway (all costs are in 2020$). 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)	1.69	30.7		28,630			
	Calculation			A/B		D×0.825^3	E/(1.05)^3	D - F
	Calculation results			0.06		16,076	13,887	14,742
15-year case	Gasoline ICEV (FUTURE TECHNOLOGY)	2.37	41.5		29,210			
	Calculation			A/B		0 (assumed)	0	D - 0
	Calculation results			0.06		0	0	29,210

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 case and FUTURE TECHNOLOGY 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 case analysis of a gasoline ICEV has a total LCD of $0.44/mi and (2) the 15-year FUTURE TECHNOLOGY case analysis of a gasoline ICEV has a total LCD of $0.29/mi. These are the same total LCD costs for gasoline ICEVs shown in for the current and future cases in Table 48 and Table 50, respectively, in Section 10. Note that there may be discrepancies in summation due to rounding shown within tables that is not present in calculations.

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} × VMT / $(1+D)^{year}$ ($)**	**Vehicle Cost (Total) ($)**
Analysis Period	**Vehicle-Fuel Pathway**						
3-year case	Gasoline ICEV (CURRENT TECHNOLOGY)	14,742	0.39				
				1	14,231	5,255	
				2	13,961	4,909	
				3	13,669	4,578	
							14,742
15-year case	Gasoline ICEV (FUTURE TECHNOLOGY)	29,210	0.23				
				1	14,231	3,127	
				2	13,961	2,921	
				3	13,669	2,724	
				4	13,357	2,535	
				5	13,028	2,355	
				6	12,683	2,183	
				7	12,325	2,021	
				8	11,956	1,867	
				9	11,578	1,722	
				10	11,193	1,585	
				11	10,804	1,457	
				12	10,413	1,338	
				13	10,022	1,226	
				14	9,633	1,122	
				15	9,249	1,026	
							29,210

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)	0.06	0.39	0.44
15-year case	Gasoline ICEV (FUTURE TECHNOLOGY)	0.06	0.23	0.29

Appendix F: Compilation of All References Used in this Report

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