Assessing Greenhouse Gas Emission and Petroleum Reduction Scenarios for the U.S. and California Transportation Sectors

Final Report

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DISCLAIMER

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Terms and Abbreviations

AEO	Annual Energy Outlook
ARB	California Air Resources Board
BAU	business-as-usual
BD	biodiesel
BEV	battery electric vehicle
BGY	billion gallons per year
Btu	British thermal unit
CA	California
CAFE	Corporate Average Fuel Economy
CH_4	methane
CI	carbon intensity
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO_2	carbon dioxide
EER	Energy Economy Ratio
EtOH	ethanol
E_{VMT}	electric mode vehicle miles travelled
EVSE	electric vehicle supply equipment
FCV	fuel cell vehicle
FFV	flex fuel vehicle
g	gram
GHG	greenhouse gas
HEV	hybrid electric vehicle
ICE	internal combustion engine
LCFS	Low Carbon Fuel Standard
LCA	Life Cycle Associates, LLC
LDA	light-duty auto
LDT	light-duty truck
MPG	miles per gallon
MJ	megajoule
MT	million tonnes
N_2O	nitrous oxide
PHEV	plug-in hybrid electric vehicle
RD	renewable diesel
RIN	renewable identification number
RFS2	Renewable Fuel Standard 2
RNG	renewable natural gas
TTW	tank-to-wheel
VMT	vehicle miles travelled
WTT	well-to-tank
WTW	well-to-wheels

Executive Summary

Significant reductions in greenhouse gas (GHG) emissions from passenger cars and light duty trucks will only be achieved by combining higher efficiency vehicles with low-carbon fuels. Both low carbon liquid fuels and electricity are more effective when coupled with fuel-efficient vehicles. Policies should encourage the continued development of both vehicle efficiency and low carbon fuels pathways to maximize long-term progress in reducing GHG emissions.

Introduction

The U.S. and the state of California (the first and fifth largest global economies, respectively) occupy central roles in the worldwide effort to reduce greenhouse gas (GHG) emissions. The U.S. and California's leadership are even more vital in the transportation sector, which unfortunately receives little attention and fewer specifics in the global accord.

Transportation is now the largest source of GHG emissions in the U.S. and light-duty vehicles—the cars and trucks that Americans drive—are the biggest contributor. Current policies in the U.S. and in California have made progress in reducing GHG emissions in light-duty transportation, but the current trajectory is not nearly adequate to accelerate progress dramatically toward climate goals.[1] In addition to policy considerations, recent years have demonstrated that economics and market forces exert significant sway in this consumer-driven sector. Sustained low gasoline prices have motivated consumers to purchase larger and less efficient vehicles and to drive their vehicles more often, halting fuel economy gains and GHG reductions in the sector at large.

Policies in the U.S. and California are a lynchpin in the global context. Light-duty vehicle and fuel technologies developed and adopted in the U.S. influence the global marketplace, but relative cost is an overwhelmingly important factor in the adoption of lower GHG vehicle technologies and fuels. Therefore, identifying the most cost-effective approach of higher efficiency and lower carbon fuels in the U.S. and California could amplify the GHG emissions reduction benefits by ensuring that significant advancements are realized beyond our borders.

With this is mind, this analysis sought answers to two key questions:

1. How much can feasible vehicle-fuel technology pathways reduce GHG emissions from light-duty transportation by 2050, in the U.S. and in California?
2. At what relative costs?

Fundamental to answering both questions is recognition that both vehicles and fuels must be addressed. For internal combustion engines, vehicle technologies are inherently constrained by the fuels that power them, and fuels are only optimized in their use by intricately designed and

[1] Under the Obama Administration, the U.S. established a goal to reduce GHG emission by at least 80% from 2005 levels by 2050 and submitted a pledge to the UNFCCC at the COP22 meeting in Paris (2015) to place the nation on a trajectory to meet that goal. This pledge has since been withdrawn by the Trump Administration. California's target is 80% from 1990 emissions by 2050.

calibrated vehicles. And whether liquid or electricity, fuels must be assessed based on their full fuel cycle, including upstream production. In this report, GHG emissions, fuel usage, and costs are estimated for the on-road fleet from 2016 to 2050. Annual emissions, fuel use and costs are summed to give cumulative on-road fleet results.

This analysis builds and expands upon the most current industry-standard tools and projections for the light-duty transportation sector. Sources include data, analysis and models from: Energy Information Administration (EIA), Argonne National Lab, National Academies of Science, U.S. Environmental Protection Agency (EPA), National Highway Traffic Safety Administration (NHTSA), and the California Air Resources Board (CARB).[2]

Promising Vehicles Technologies

The first step was to bound the analysis to future vehicle technologies that foreseeably could: 1) achieve the GHG emissions reductions targets for both the U.S. and California, and 2) feasibly scale to substantial market share by 2050. Using today's fuels—gasoline and the current electricity mix—no vehicle technology pathway meets the U.S. 80% reduction goal in 2050 (corresponding to an on-road fleet average goal of 86 g CO_2 equivalent/mile) even though electric technologies are today considerably more fuel efficient than internal combustion engine (ICE) vehicles. With lower-carbon cellulosic ethanol and a low-carbon electricity grid, only electrified vehicle platforms—hybrid electric vehicles (HEV), plug in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) or fuel cell vehicles (FCV) with or without an internal combustion engine (ICE) achieve the target. This is shown clearly in Figure 1. Accounting for cost, which significantly handicaps the prospects for hydrogen fuel cell vehicles through 2050, the electrified platforms battery electric, plug-in hybrid electric, and hybrid electric are the most feasible GHG reduction options. But the market dominance of ICEs bears substantial influence over the progress to 2050.

Light-duty vehicle sales continue to be dominated by the lowest cost option: gasoline ICEs. This is projected to continue through 2025 and beyond, as automakers continue to improve ICE fuel economy at relatively low incremental costs compared to electrification. Electric vehicle costs—particularly batteries—have started to drop substantially and are projected to further decrease as electric vehicle sales increase.

ICE technologies are projected to reach their highest fuel efficiency potential around 2025-2030 with the fuels of today if the Obama era 2022-2025 CAFE standards were fully enacted. Conversely, if the Trump Administration's Safer Affordable Fuel Efficient Vehicles rule (SAFE) is implemented, it would effectively delay the advancement of ICE technologies and the accompanying improvements in fuel efficiency. Further GHG reductions beyond the CAFE standards will only be achieved with lower-carbon liquid fuels as shown in Figure 1 or by employing measures like downsizing vehicles, changing fleet mix to more passenger vehicles or

[2] EIA Annual Energy Outlook 2016; Argonne National Lab VISION2015 model, Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model, and Cradle-to-Grave Lifecycle Analysis of U.S. Light Duty Vehicle Fuel Pathways (2016); National Academies of Science Transitions report (2013); EPA-NHTSA Draft Technical Assessment Report, EPA Fuel Economy Guide, CARB VISION2.1 and CA-GREET2 models

by reducing vehicle miles traveled. This is also true for electric vehicles. While they are much more efficient than ICEs, they are currently powered by a U.S. grid which is more carbon-intensive than gasoline.

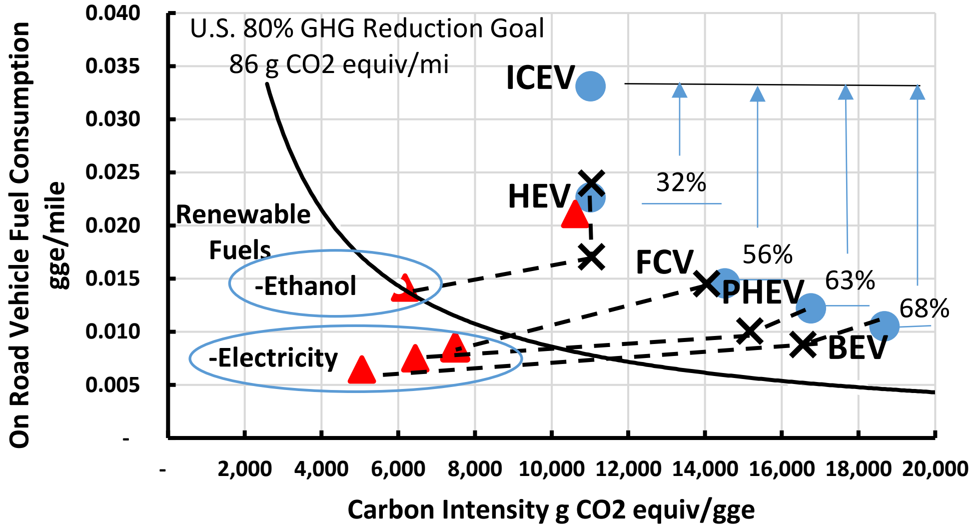

Figure 1. Passenger vehicle on road fuel consumption and fuel carbon intensity for ICEV, HEV, FCV, PHEV, and BEV for 2016 ● 2025 **X** 2050 ▲. Vehicle fuel consumption improvements shown for 2016 technologies. Only vehicles using renewable fuels meet or exceed U.S. goal of 80% GHG reduction—86 g CO_2 equivalent/mile.

To better understand the tradeoffs of vehicle efficiency, fuel carbon intensity, and costs, this analysis compared various aggressive fuel-vehicle scenarios for the cars and trucks in the light duty transportation sector through 2050.

Scenarios for 2050

Continued domination of gasoline ICEs worldwide out to 2050 formed a "business as usual" case to compare against scenarios based on the most feasible large-scale combinations of vehicle electrification and liquid fuels (gasoline and ethanol blends). The "business as usual" case was based on proposed fuel economy standards as of the time the analysis was conducted. These Corporate Average Fuel Economy standards (CAFE), set fuel economy standards through 2025 and were finalized by EPA and CARB. However, in recognizing that the Trump Administration has since proposed the SAFE rule, we have also added an analysis of a separate "business as usual" case scenario based on this rule.

Each alternative scenario centered on a dominant vehicle technology from the most promising identified by the initial analysis, constrained by practical limitations and the attributes of cars versus trucks or SUVs, with the balance of vehicles not suitable for battery electric propulsion assumed to be ICEs. The four primary scenarios include the following vehicle types:

- Battery electric vehicles (**BEV**) with sales limited based on charging infrastructure and vehicle attributes like size, payload, and range

- Plug-in hybrid electric vehicles powered by gasoline and electricity (**PHEV**, e.g. Chevy Volt) with slightly higher penetration than BEVs because PHEVs can operate on either fuel
- Plug-in hybrid electric vehicles fueled with ethanol (**E85 PHEV**) in lieu of gasoline
- Hybrid electric vehicles (e.g. Toyota Prius) using E85 ethanol (**E85 HEV**)

Recognizing the interdependency of fuels and vehicle technologies to total GHG emissions reductions, as well as potential for higher costs, the analysis considered both base case and low carbon intensity fuels. The base case fuels are those in use today, with incremental reductions in carbon intensity projected over time. The low carbon scenarios assumed a 70% non-fossil fuel electricity grid and that half of the ethanol used would be derived from cellulosic material, and half from corn, by 2050.

Potential GHG Reductions

While individual BEVs and PHEVs fueled with low carbon fuels can meet or exceed the individual vehicle targets, none of the scenarios reduce fleet GHG emissions in light-duty transportation by 80% by 2050 as shown in Figure 2 for the U.S. and California markets.

None of the scenarios achieve the 80% reduction even with the aggressive market penetration assumptions. In both the U.S. and California, continuing the “business as usual” trajectory—dominated by gasoline ICEs in which engine technology development and efficiency are constrained by the fuels currently in the marketplace—produces the least GHG reductions. Conversely, all alternative technology scenarios significantly improve upon the status quo but fall short of the goal due to the time required for fleet turn over.

In the U.S. analysis, each low-carbon fuel pathway provides greater GHG reductions than any of the base fuel scenarios. This reiterates the imperative of addressing both vehicles and fuels to maximize GHG reductions in light-duty transportation. Of the alternative scenarios, the low-carbon battery electric and E85 PHEV options provide the greatest GHG reductions overall. These are also the best alternatives for GHG emissions reductions in cases where the low-carbon fuel pathways fail to fully materialize in the U.S.

In California, “business as usual” GHG emissions decrease substantially compared to the U.S. at large, due to strong state policy measures: the Zero Emission Vehicle mandate, the Low Carbon Fuel Standard (LCFS), and a lower-carbon electricity grid. This results in less variation in GHG reductions between the alternative technology scenarios. The base and low-carbon cases provide very similar results. The low-carbon battery electric and E85 PHEV pathways result in slightly greater reduction and nearly meet the 2050 goal.

Table 1 summarizes the scenario analyses for the U.S. and California along with the 2050 GHG emissions to achieve an 80% reduction from the baseline year. For each scenario average on road fleet fuel economy in 2050 is shown as well as estimated light duty fleet GHG emissions and percent reduction from the GHG baseline for base fuels and low carbon fuels.

Both the U.S. and California results illustrate that:

- Low-carbon liquid fuels (in this case high ethanol blends) and low-carbon EV technologies achieve comparable GHG reductions.
- Low-carbon fuels coupled with efficient powertrain technologies provide the largest GHG reductions
- Vehicle electrification will be needed to improve ICE vehicle efficiency.

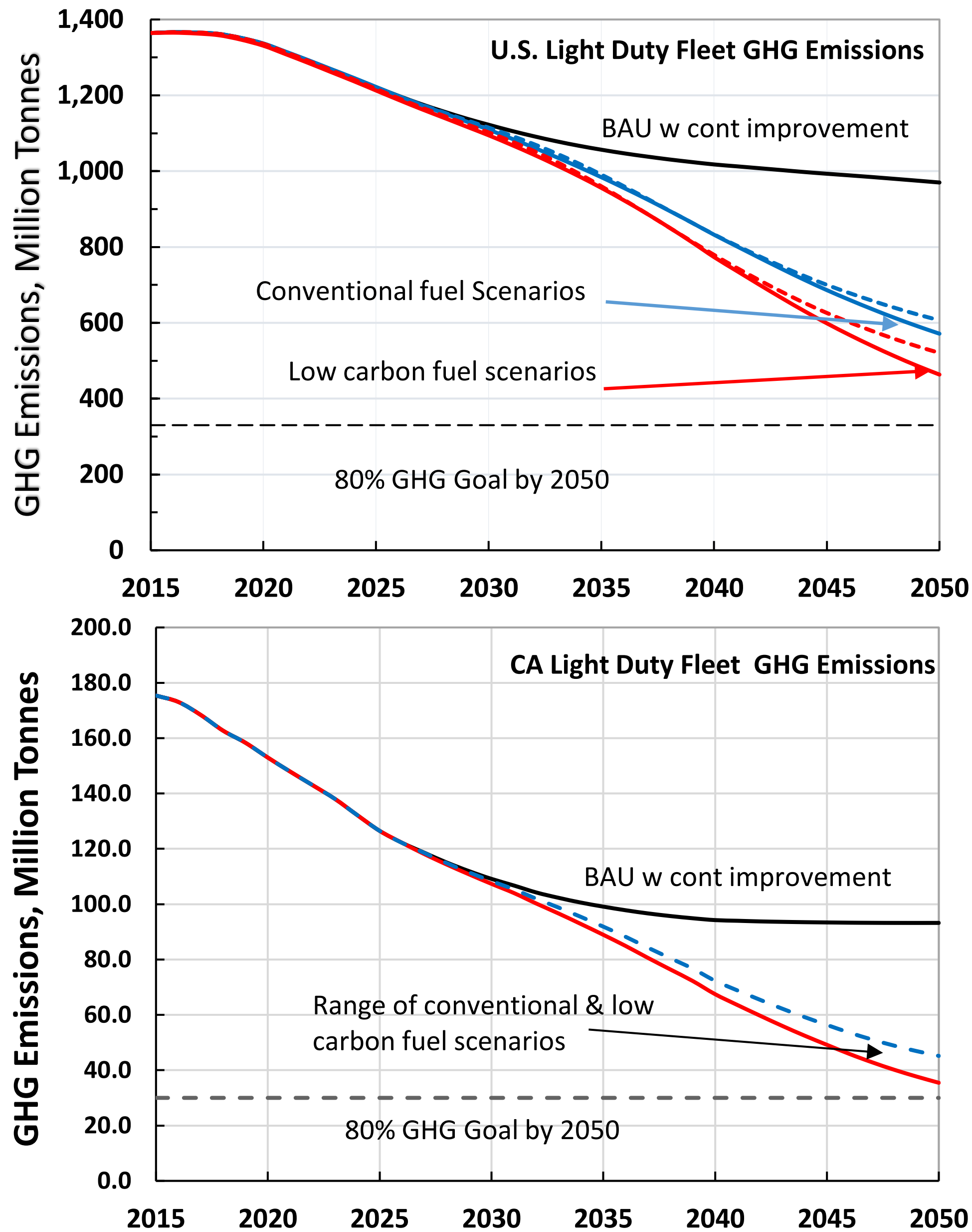

Figure 2. Possible U.S. and California GHG emission reductions for business as usual (BAU) with continuing efficiency improvements compared to the reductions possible with electrified vehicle technologies using todays fuels and low carbon fuels. The scenario results show HEV in dashed line and BEV in solid line. PHEV scenario results are between the HEV and BEV results.

Table 1. Comparison of GHG reductions for U.S. and California

Scenario	On Road Fleet Fuel Economy in 2050 (mpg)	Base Fuels		Low Carbon Fuels	
		GHG Emissions in 2050 (Million Tonnes)	% GHG Reduction	GHG Emissions in 2050 (Million Tonnes)	% GHG Reduction
UNITED STATES LIGHT DUTY FLEET					
BAU w/cont FE 2025+	42.5	970	41.2%	970	41.2%
E85 HEV	57.8	606	63.3%	521	68.4%
E10 PHEV/E85 HEV	66.3	598	63.8%	493	70.1%
E85 PHEV/E85 HEV	68.3	554	66.4%	445	73.0%
BEV/E85 HEV	69.3	571	65.4%	431	73.9%
80% Reduction Goal	**--**	***330***	***80.0%***	***330***	***80.0%***
CALIFORNIA LIGHT DUTY FLEET					
BAU w/cont FE 2025+	44.0	93.2	37.9%	93.2	37.9%
E85 HEV	64.4	45.2	69.9%	42.0	72.0%
E10 PHEV/E85 HEV	76.0	45.1	69.9%	42.3	71.8%
E85 PHEV/E85 HEV	78.0	39.4	73.7%	36.0	76.0%
BEV/E85 HEV	83.3	39.0	74.0%	35.5	76.3%
80% Reduction Goal	**--**	***30.0***	***80.0%***	***30.0***	***80.0%***
CA 1990 GHG Emissions	150	million tonnes			
US 2005 GHG Emissions	1650	million tonnes			

GHG Reductions Versus Costs

The likelihood and feasibility of success of climate-related policy measures will be strongly determined by economics. Consequently, cost effectiveness is an essential measure to fully inform the policy debate. Compared to the baseline “business as usual,” the U.S scenarios show a narrow variation in GHG emission reductions and higher variation in costs per tonne (Table 2). This is a result of differences in vehicle costs and fuel savings. Lower vehicle costs for HEVs are partially offset with less fuel savings compared to BEVs or PHEVs. Low-carbon fuel costs reflect the higher assumed costs of cellulosic ethanol.[3] Cellulosic ethanol costs have a significant impact on cost effectiveness for the U.S. scenarios and much less of an effect for the California scenarios. Scenarios that rely more on liquid fuel (e.g. E85 HEV) are more affected by the higher fuel cost.

Plotting the relative cost effectiveness and GHG emissions reductions provides a clearer view of the tradeoffs between GHG reductions and cost for the U.S. (Figure 3). All scenarios but one provide a cost savings compared to the BAU. Low-carbon scenarios provide more cumulative GHG reductions but provide smaller cost savings (with one low-carbon scenario increasing costs relative to the BAU). The E85 HEV scenario is the most cost-effective pathway for moderate reductions as well as the most cost-effective low-carbon fuel pathway, followed by the BEV scenario. The PHEV scenarios have higher cost per tonne.

[3] Costs of producing low-carbon ethanol may decrease further as producers gain experience and/or adapt new technologies

Table 2. U.S. and California cost per tonne of GHG reduction and cumulative GHG reduction compared to Business as Usual

	Base Fuels		Low Carbon Fuels	
	Cost per tonne ($/tonne)	Cumulative Reduction (Billion tonnes)	Cost per tonne ($/tonne)	Cumulative Reduction (Billion tonnes)
U.S.		Billion tonnes		Billion tonnes
BEV/E85 HEV	-85	5.0	-33	6.9
PHEV/E85 HEV	-55	4.7	-13	6.3
E85 PHEV/E85 HEV	-41	5.1	1	6.7
E85 HEV	-173	4.7	-81	5.9
California		Million tonnes		Million tonnes
BEV/E85 HEV	-61	648	-54	682
PHEV/E85 HEV	-33	597	-27	626
E85 PHEV/E85 HEV	-10	667	-4	703
E85 HEV	-128	572	-109	603

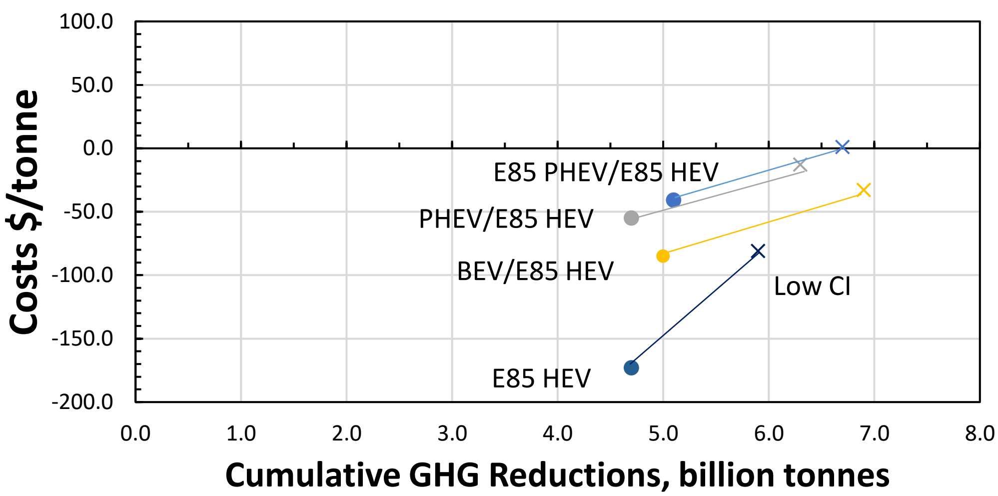

Figure 3. Cost effectiveness vs cumulative GHG reduction, U.S. analysis

California's low-carbon pathways do not result in significantly more GHG reductions than its base case fuels (Figure 4). The BEV and E85 PHEV scenario offer the greatest GHG abatement at a cost savings from $54-$60 per tonne for BEVs and $3-$7 per tonne for PHEVs. The HEV scenario provides the most cost savings and has the lowest GHG reduction. The battery electric scenario is among the highest GHG reduction and with cost savings about half of the HEV scenario. The PHEV scenarios provide comparable GHG reductions to the BEV scenario but at higher costs (almost the same as the BAU scenario).

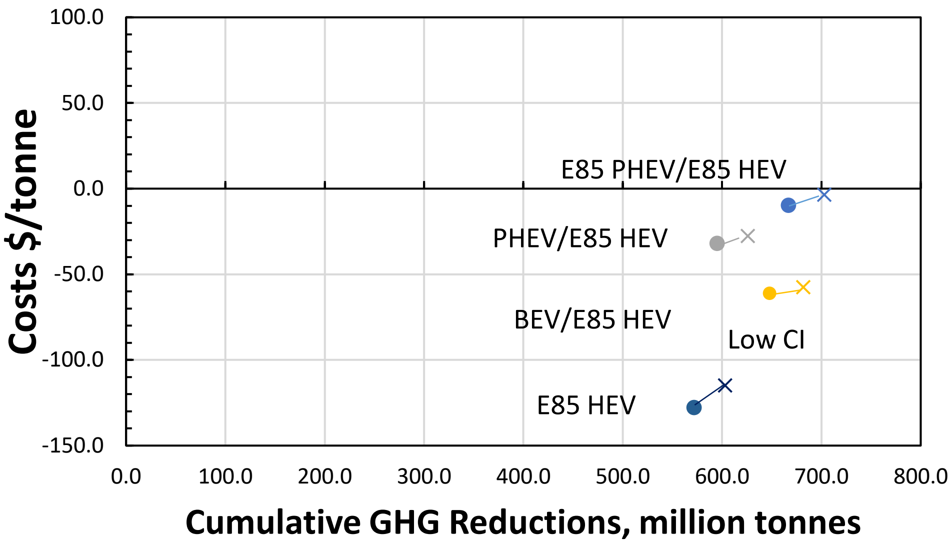

Figure 4. Cost effectiveness vs cumulative GHG reduction, California analysis

The California results show that the various combinations of fuel and vehicle technologies provide similar cumulative GHG reductions at a wide range of costs. Plug in electric vehicles have the highest projected costs and hybrid electric vehicles have the lowest projected costs.

It is important to note that the low-carbon pathways for both electricity and liquid fuel face significant hurdles to reach the necessary market share for maximum GHG reductions, in particular in the U.S. at large. The low-carbon electricity scenarios assumed a 70% non-fossil fuel U.S. electricity grid by 2040, including zero coal generation. A National Renewable Energy Laboratory (NREL) study did find 80% renewable electricity feasible in the U.S. by 2050 but noted that it would require a transformation of the entire electricity system.[4] This challenge becomes even more difficult since the Trump Administration has proposed elimination of the Clean Power Plan (CPP). Our analysis showed that eliminating the CPP increases projected 'business as usual' carbon emissions from electricity by 22% in 2050. While this analysis did not consider the implications for the low-carbon pathways, absence of the CPP could decrease the prospect of achieving 70% non-fossil electricity by 2040.

The likelihood of producing cellulosic ethanol volumes necessary to achieve the low-carbon liquid fuel pathways is perhaps more daunting. A 50% share for cellulosic ethanol would require 10 to 27 billion gallons for the U.S. For context, 2016 total U.S. production amounted to just 3.8 million gallons, despite total nameplate plant capacity of more than 50 million gallons and generous financial incentives. The Department of Energy's Billion Ton Report catalogs ample

[4] "… transformation of the electricity system would need to occur to make this future a reality. This transformation, involving every element of the grid, from system planning through operation, would need to ensure adequate planning and operating reserves, increased flexibility of the electric system, and expanded multi-state transmission infrastructure, and would likely rely on the development and adoption of technology advances, new operating procedures, evolved business models, and new market rules." Executive Summary, NREL Renewable Electricity Futures Study, https://www.nrel.gov/analysis/re_futures/

cellulosic feedstocks in the U.S.,[5] but does not assess the technical feasibility of fuel production. Current indications are that, unlike renewable electricity which has advanced to full-scale commercialization, cellulosic ethanol remains a century-old fledgling technology of more promise than fruition.

Other key findings:

- Both the U.S. and California committed some time ago to reducing petroleum use, for national security and environmental reasons, respectively.[6] On this measure, both are on track to make significant progress by 2050. BAU prior to the SAFE fuel economy proposal reduces U.S. annual petroleum use in light-duty transportation by 24-30% and 43-48% in California by 2050. The various scenarios reduce petroleum use by 71 to 78% in the U.S. and by 82 to 87% in California[7].

- For the U.S. and California, a large-scale introduction of E85 HEVs requires an increase in ethanol consumption from the current 14 billion gallons (1.5 billion gallons California) per year to nearly 52 billion gallons (4.5 billion gallons California) in 2050. The base case assumes most of the ethanol is produced from corn and the low-carbon case has 50% from cellulosic for the U.S. and 66% for California by 2050.

- With low carbon fuels, the BEV and PHEV scenarios can achieve the U.S. national 2050 goal if technology roll-in rates increase above the modeled business as usual before 2025; if roll-in rates are even more aggressive than assumed; or if the grid decarbonizes more quickly than assumed.

- BEV range, infrastructure, and other issues affecting market acceptance will be factors determining whether BEVs can achieve large enough sales volumes to significantly reduce GHG emissions.

- The proposed Safer Affordable Fuel Efficient (SAFE) vehicles rule delays implementation of more efficient technologies by 10 years. This results in SAFE BAU cumulative GHG emissions increasing by 2 billion tonnes for the U.S. light duty market. The alternative scenarios are affected even more by the delay, with the SAFE analyses increasing cumulative GHG emissions by 6 billion tonnes. Compared to the 80% reduction goal, these SAFE alternative scenarios reduce GHG emissions 48% by 2050 compared to the

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[5] DOE Billion Ton Report https://www.energy.gov/eere/bioenergy/downloads/2016-billion-ton-report-advancing-domestic-resources-thriving-bioeconomy

[6] The U.S. effort to reduce petroleum use has been implemented by Corporate Average Fuel Economy (CAFE) standards and legislation including the 2007 Energy Independence and Security Act (EISA). In California, Governor Brown made a 50% reduction in petroleum use by 2030 a goal for his administration. (https://www.arb.ca.gov/newsrel/petroleum_reductions.pdf)

[7] In the 2018 NPRM for the SAFE rule, the federal agencies proposed to withdraw California's ability to set fuel economy standards separate from the national standards (see p. 31 of SAFE NPRM "Proposed Withdrawal of California's Clean Air Act Preemption Waiver"). While current California and Federal fuel economy standards are the same, successful elimination of California's preemption waiver would restrict the state's ability to influence national fuel economy standards and prevent it from setting its own. This could affect California's ability to meet its emissions reduction goals.

base fuel scenarios reductions of 65.4%. Fuel use for the SAFE BAU increases by 200 billion gge relative to the BAU and by 526 billion gallons for the EV scenarios. The SAFE program also increases consumer spending by over $500 billion relative to the BAU.

Policy context & takeaways:

- Relaxation or delay of the standards previously established for 2022-2025 as proposed in the SAFE Rule affects the business as usual projections in this analysis, and also lowers the cumulative GHG reductions that can be expected from any of the scenarios

- Market economics will exert strong influence over the success of measures to reduce GHG emissions in U.S. and California light-duty transportation, in multiple ways and with unpredictable outcomes. The recent low gasoline prices have demonstrated the sway of market forces. The dramatic drop in electric vehicle purchases in Georgia after eliminating the state's subsidy highlight the vulnerability of emerging vehicle technologies to even marginal policy incentive schemes.[8]

- Pursuing multiple technology pathways is an important hedge to provide flexibility as circumstances change. Whether market forces intervene, politics change, technology evolves, or breakthroughs occur, policies should build in the flexibility for stakeholders to adapt and comply. Policies and the regulations that enact them should support multiple ambitious GHG emissions reduction pathways. For instance, deployment of electric (either BEV or PHEV) vehicle technologies and facilitating the use of low-carbon, high-octane ethanol blends in lieu of regular grade gasoline provides flexibility. Earlier or more rapid introduction of favorable technologies is key.

- In an era of rapid technological change only beginning to take hold in transportation, the status quo may shift dramatically within a relatively short period of time. For instance, the advent of autonomous vehicles can upend expectations in unpredictable ways. Keeping a diverse set of powertrain and fuel technology options on the table can allow for the most flexibility in meeting goals for the light-duty transportation system.

- Due to strong climate policy measures, California is much closer to achieving the 2050 goal than the U.S. However, without additional actions, the current policies (our modeled BAU) will only get California halfway. More aggressive deployment of advanced vehicle technologies and low-carbon fuels nearly meet the goal; however, overall costs and consumer acceptability remain significant hurdles. A more flexible and diverse strategy could achieve ambitious GHG emissions reductions and solidify California's climate leadership while providing more accommodation for consumer preferences and affordability.

- The SAFE proposal to strip California of its waiver to establish more ambitious standards than the U.S. at large—and thus the ability of other states to follow California's lead—

[8] BEV sales dropped off dramatically, despite continued availability of the much larger federal credit of $7500

could delay or stymie progress for the large portion of the U.S. committed to aggressively reducing GHG emissions in light-duty transportation.

- These results indicate that for the U.S. to meet GHG reduction goals and retain its global influence in transportation, both vehicles and fuels must be addressed. The low-carbon scenarios show that the greatest progress can be made by enabling advanced vehicle technologies with low-carbon fuels, and can even do so while saving the consumer money relative to business as usual.

- Many factors and challenges will exert significant influence over the relative success of efforts to reduce GHG emissions in light-duty transportation in the U.S. These may include:

  - Continued progress in vehicle fuel economy and tailpipe CO_2 standards
  - Commitment to and substantial investment in fueling (and charging) infrastructure
  - Growing the biofuel industry and fostering its innovation, particularly cellulosic ethanol
  - Greater deployment of high-octane fuels such as E85 and E30
  - Removal of regulatory barriers to greater use of higher ethanol blends
  - Continued decarbonization of the electricity grid
  - Measures to encourage aggressive development and deployment of advanced vehicle technologies.
  - The technical hurdles to commercialization of cellulosic ethanol have so far remained insurmountable, despite well-financed attempts, particularly in the U.S.[9]

[9] DuPont recently announced its intention to sell its Iowa cellulosic plant, without ever successfully producing fuel for sale

1. Introduction

The transportation sector generates approximately 30% of U.S. greenhouse gas (GHG) emissions; therefore, reducing emissions from vehicles and the production of fuels is an essential component of a national GHG reduction strategy. Consequently, both California and the U.S. have established challenging GHG reduction goals. The Paris Agreement signed by the Obama Administration committed the U.S. to reduce GHG emissions by 26-28% from 2005 levels by 2025[10]. The Obama Administration's long-term target was an 80% reduction from 2005 levels by 2050, matching that of the 2009 American Clean Energy and Security Act (Waxman-Markey)[11] that passed the U.S. House of Representatives but failed in the Senate. While the U.S. commitment has come into question with the Trump Administration's stated intention to exit the Paris Accord, California remains unwavering. The California GHG reduction goal codified in the Global Warming Solutions Act[12] is to reduce emissions to 1990 levels by 2020. A subsequent bill codified an interim GHG reduction goal of 40% below 1990 levels by 2030. The Governor has also set a target of reducing GHG emissions to 80% below 1990 levels by 2050.

Transportation accounts for nearly 70% of U.S. petroleum use. Figure 1-1 shows the distribution of energy used in the U.S. transportation sector in 2015. Most of the fuel (76%) was consumed on-road. Of this total, more than 70% is used by light-duty cars and trucks. The overall objective of this study is to perform an analysis of the U.S and California light-duty vehicle fleets to determine how the 2050 goals might be achieved, and to quantify the corresponding changes in consumer spending on fuel and vehicles. The effects on petroleum consumption and ethanol use are also quantified.

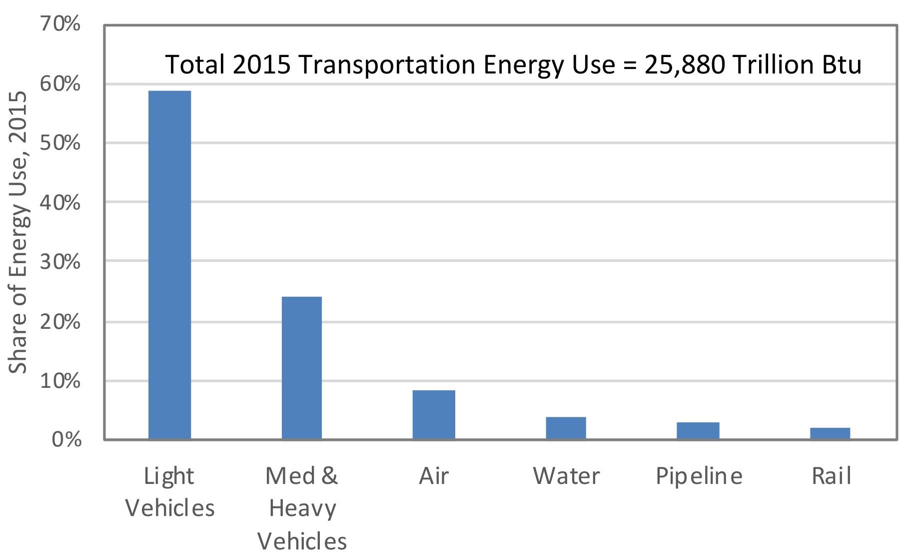

Figure 1-1. Transportation Energy Use by Mode, 2015

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[10] http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx

[11] https://www.congress.gov/bill/111th-congress/house-bill/2454

[12] Assembly Bill 32, 2006. Codified in CA H&S Codes 38500, 38501, 28510, 38530

1.1 Light-duty GHG Emission Reduction Measures

There are three ways to reduce light-duty GHG emissions: improve vehicle fuel economy, reduce fuel carbon content, and reduce vehicle miles travelled (VMT). Although VMT reduction measures such as increased public transit, ridesharing, and pay-as-you-go insurance are an important piece of the solution, this study focuses on reductions that can be achieved from improved fuel economy and use of lower carbon fuels.

The federal government currently limits light-duty GHG emissions through joint rulings[13] by the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA). A joint 2010 rule sets Corporate Average Fuel Economy (CAFE) and GHG standards for new light-duty autos and trucks to 34.1 mpg (250 g CO_2/mi) by 2016. A subsequent joint rulemaking in 2012 set a 163 g CO_2/mi CO2 by model year 2025. NHTSA has set fuel economy standards through 2021, however an augural value based on the EPA CO2 standard for 2025 is 54.5 mpg. The 2012 ruling stipulates an interim review of the standards for model years 2022-2025. In July 2016, EPA, NHTSA and ARB issued a draft Technical Assessment Report to support this interim review, formally known as the Midterm Evaluation. In January 2017, EPA issued its final determination that "automakers are well positioned to meet the standards at lower costs than previously estimated" and retained the existing CO2 standards "despite a technical record that suggests the standards could be made more stringent." However, in April of 2018 the EPA determined that these standards "are not appropriate" and "should be revised" while announcing that it in partnership with NHTSA it will initiate a new notice and comment rulemaking to "further consider appropriate standards for MY 2022-2025 light-duty vehicles." [14]

The final standards are provided in Figure 1-2. For 2012-2025 there are four separate standards that depend on the vehicle's footprint. The actual fuel economy standard is therefore a sales weighted average by footprint grouping. Note that the actual fuel economy of light-duty autos is better than the standard, while the actual light truck fuel economy just meets the standard. In 2012, EPA and NHTSA estimated that the fleet average fuel economy for 2025 would be 54.5 mpg. The revised estimate in the Midterm Evaluation is 50 mpg due to a consumer shift away from light autos towards light trucks.[15]

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[13]NHTSA: 49 CFR Parts 531, 533, 536, 537 and 538; EPA: 40 CFR Parts 85, 86, and 600

[14] April 2018, EPA, "Notice of Intention to Reconsider the Final Determination of the Mid-Term Evaluation of Greenhouse Gas Emissions Standards for Model Year 2022-2025 Light Duty Vehicles"

[15] The increased sales of light duty trucks are driven in part by low gasoline prices.

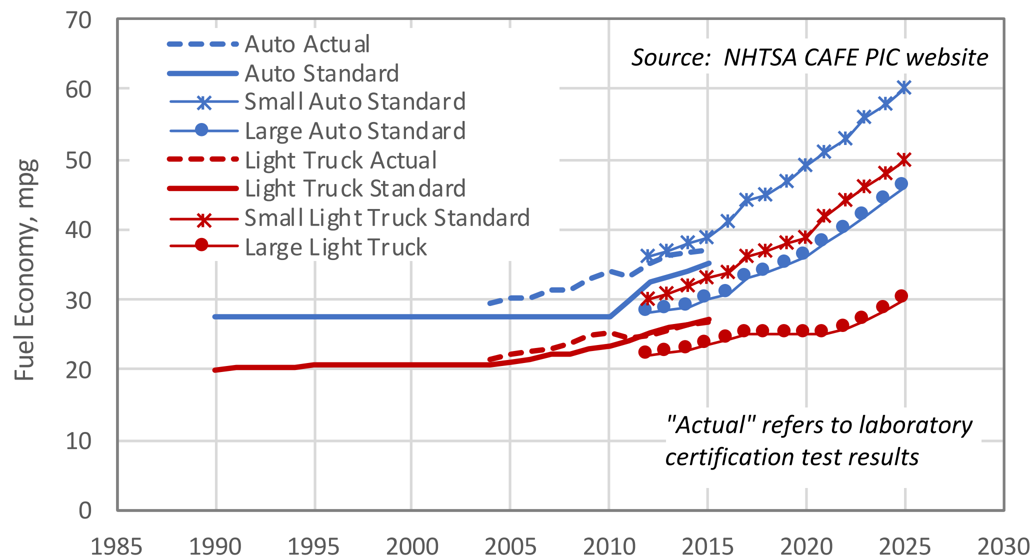

Figure 1-2. CAFE standards and fuel economy achieved or projected

Another federal regulation that limits GHG emissions from the light fleet is the Renewable Fuel Standard (RFS). The RFS was created under the Energy Policy Act of 2005 and subsequently expanded by the Energy Independence and Security Act of 2007. The RFS requires obligated parties (refiners and fuel importers) to provide set volumes of four different types of fuel each year as indicated in Figure 1-3. By 2022, 36 billion gal/yr of renewable fuel are mandated.

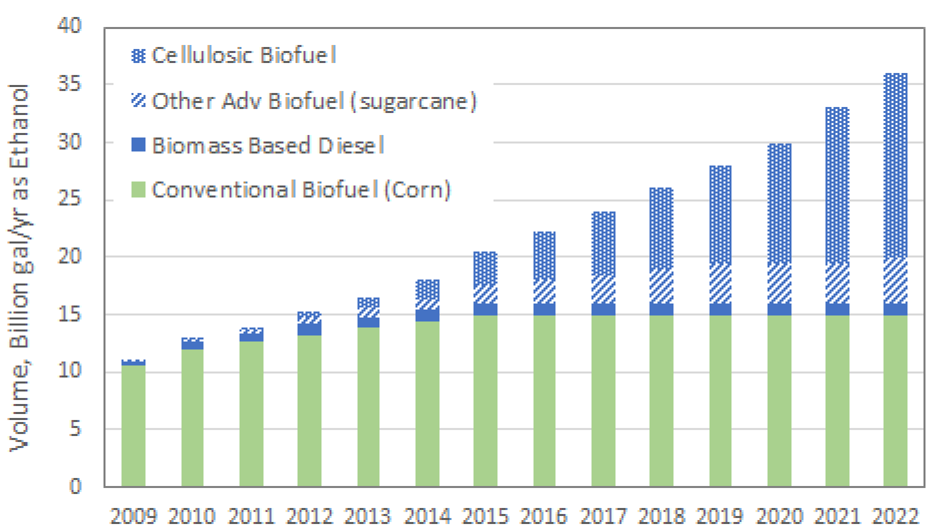

Figure 1-3. Original RFS renewable fuel volume requirements

The four different renewable fuel categories are summarized in Table 1-1. Each ethanol equivalent gallon of renewable fuel produced generates a renewable identification number (RIN) with a “D-Code”. The D-Code assigned depends on the feedstock type, fuel type and lifecycle GHG reduction achieved relative to baseline petroleum. Obligated parties must submit a certain number of each type of RIN each year to demonstrate compliance. RINS can be acquired by purchasing renewable fuel with RIN attached or may purchase RINS on the market.

In recent years, EPA has reduced the volume requirement for advanced and cellulosic biofuels due to commercialization delays. For example, the 2017 volume for cellulosic ethanol is 311 MGY compared to the originally required volume of 5.5 BGY. EPA classifies CNG produced from renewable natural gas as cellulosic biofuel, so this has generated the bulk of the D3 RINS in the past several years. Obligated parties may also purchase cellulosic waiver credits rather than purchasing D3 RINS. The RFS volumes were originally set through 2022, but the rule technically does not expire, and EPA can continue to require renewable fuel sales beyond 2022.

Table 1-1. RFS fuel categories

	Minimum GHG Reduction	RIN D Code
Cellulosic Fuel	60%	3
Biomass Based Diesel	50%	4
Advanced Biofuel	50%	5
Conventional Biofuel	20%	6

An alternative to the RFS mandate approach to reducing fuel carbon intensity is a Low Carbon Fuel Standard (LCFS). An LCFS requires the average carbon intensity (CI) of transportation fuel to decrease over time. In the absence of a federal standard, California adopted an LCFS[16] which requires obligated parties (fuel suppliers and blenders) to reduce transportation fuel well-to-wheel carbon intensity 10% from 2009 levels by 2020. **Error! Reference source not found.** provides the original compliance curve as stated in the 2009 standard and the modified curve resulting from litigation and subsequent re-adoption in 2015. The figure also shows actual fuel carbon intensity through 2015. Obligated parties have been well below the required CI levels through 2015, likely due to credit banking provisions in the rule. By over-complying in early years, obligated parties can generate surplus credits which may either be sold to other obligated parties or saved for compliance in future years.

[16] The LCFS was an early action item under AB32, the Global Warming Protection Act. ARB adopted the LCFS in 2009, amended it in 2011 and readopted it in 2015. The final regulation order may be found here: https://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

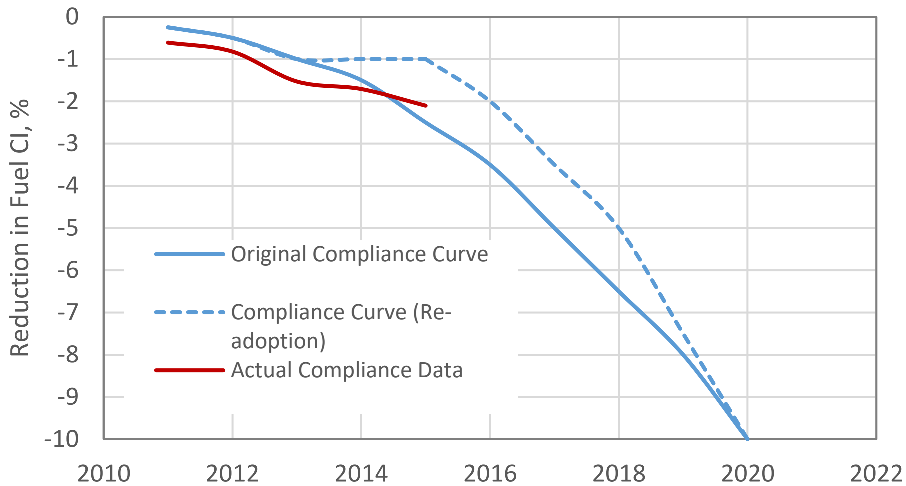

Figure 1-4. California LCFS GHG reduction targets

Another policy to reduce vehicle GHG emissions in California and nine other states[17] is the Zero Emission Vehicle (ZEV) Mandate. Automobile manufacturers are required to generate ZEV credits through the sale of electric drive vehicles; a set number of credits must be created per total vehicles sold. For every 100,000 vehicles sold in these states, 4500 credits must be generated in 2018 increasing to 22,000 credits by 2025. The number of credits generated for each vehicle depends on electric range. Plug-in hybrid electric vehicles (PHEVs) receive 0.4-1.3 credits while battery electric vehicles (BEVs) receive up to 4 credits depending on electric range. Since there is not a 1:1 ratio between credits and vehicles, it is hard to forecast the number of ZEVs sold. ARB's most recent forecast[18] indicates that in 2025, nearly 8% of ZEV state light vehicles will be ZEVs and PHEVs.

1.2 Scope of Present Analysis

EPA published a wedge analysis[19] of the U.S. transportation sector to determine what technologies could substantially reduce GHG emissions. The analysis projected business-as-usual (BAU) GHG emissions through 2050 and identified technologies and measures needed to stabilize emissions at 2006 levels as well as additional measures that could reduce emissions below 2006 levels.

In this analysis, GHG emissions from the U.S. and California light-duty fleet are forecast through 2050, considering current CAFE standards, the RFS, the LCFS and ZEV Mandate. To establish a baseline to evaluate economic effects, incremental spending on vehicles (relative to conventional 2015 gasoline vehicles) and fuel spending are quantified. These updated light-duty BAU cases are then compared to the federal and California GHG emission reduction targets to assess projected progress. The range of feasible vehicle-fuel technology combinations to further reduce GHG emissions was evaluated for their individual potential to achieve 2050

[17] Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont
[18] 2017 ZEV Calculator Tool https://www.arb.ca.gov/msprog/zevprog/zevcalculator/zevcalculator.htm
[19] A Wedge Analysis of the U.S. Transportation Sector, EPA420-R-07-007, Mui, Alson, Ellies, Ganss, June 2007

climate goals. Based on the most promising combinations, alternative scenarios were developed utilizing advanced vehicles and low carbon fuels to determine if the GHG targets might be achieved nationally and in California, and to estimate the corresponding vehicle and fuel costs relative to BAU.

This analysis evaluates a variety of options to reduce GHG emissions from the light-duty fleet, including:

- Improve gasoline internal combustion engine (ICE) vehicle efficiency
- Use of mild hybrid technology
- Improve vehicle aerodynamics and vehicle mass reduction
- Use high-octane ethanol fuels in dedicated and conventional ICE vehicles
- Increase use of hybrid electric vehicles
- Increase use of battery electric and fuel cell vehicles
- Reduce the carbon intensity (CI) of fuels

Efforts are well underway by automakers to improve ICE vehicle efficiency to meet current and proposed CAFE standards. Automakers are bringing considerable innovation to gasoline ICE vehicles with improvements being made in engine technology, transmissions, accessory loads, drag, and vehicle weight. Key gasoline engine technologies being pursued include cylinder deactivation, variable valve lift, direct injection (allows higher compression ratio and enables downsizing and boost), different combustion cycles and mild hybrids. Adding gears to the automatic transmissions (6-8 gears) and continuously variable transmissions also provide significant fuel economy benefit. Other improvements include powering accessories with battery electricity to reduce parasitic engine load, reducing aerodynamic drag, and utilizing low rolling resistance tires. Although these technologies are not evaluated individually, we have assumed that automakers will implement many of these technologies to achieve the proposed 2025 CAFE standards.

Gasoline is currently a 10% volume blend of ethanol with gasoline blendstock. Because ethanol increases octane, the blendstock octane rating has decreased as ethanol volume has increased, maintaining pump octane at 87 for regular gasoline. One option automakers are considering is to design vehicles to operate on mid- (in the range of 20-40% ethanol, but generally discussed as E30) and high- (up to 85% ethanol, known as E85) level blends. Dedicated vehicles that operate exclusively on E30 or E85 could be optimized for the higher-octane fuel by increasing compression ratio without having to retard the spark timing. The increased power output would allow engines to be downsized, improving fuel economy. Moreover, ethanol promotes rapid combustion which results in cooler exhaust, increasing the tolerance for exhaust gas recirculation.

Hybrid electric vehicles (HEVs) have two different power sources: a downsized engine and a battery. The battery can assist the smaller engine when needed. The gasoline engine is shut off when motive power is not needed (coasting, idling, stopped). Most hybrids have regenerative braking to capture heat lost in braking and store it as electricity in the battery. HEVs are mostly seen in the light auto versus light duty truck sector since batteries are quickly depleted when towing or carrying large loads. Without battery power the downsized engine does not have the horsepower needed for these light duty truck applications.[20] Most current HEVs are so-called power split HEVs with a main motor-generator driving the transmission and the gasoline engine either providing additional power to the main motor generator or charging the battery.

Plug-in electric vehicles (PHEVs) are like HEVs except they have a larger battery that allows all-electric vehicle operation for 10-50 miles. Unlike HEVs, PHEVs can be charged via a plug to external source, as well as fill up at the gasoline pump. Full battery electric vehicles (BEVs) operate only on battery power; the batteries are plugged to an external power source to recharge. Hydrogen fuel cell vehicles (FCVs) are like BEVs except they carry hydrogen tanks and fuel cells to convert hydrogen to electricity for motive power.

Improvement in ICE fuel economy can be coupled with reduced CI fuel. For example, ethanol can be made from cellulosic feedstocks rather than corn, compressed natural gas (CNG) vehicles can use renewable natural gas (RNG) rather than fossil natural gas, and diesel vehicles can use more biodiesel. Vehicles with internal combustion engines (ICEs, HEVs, and PHEVs) can increase the amount of ethanol from 10% by volume in gasoline to a mid-level blend (30%) up to a high-level blend (85%). Vehicles using electricity can benefit from a lower-carbon power grid.

This analysis forecasts BAU GHG emissions for the U.S. and California light fleets incorporating the most up-to-date data and research on fuel economy for different vehicle technologies, conventional and alternative fuel well-to-wheels carbon intensity estimates, and vehicle and fuel technology costs. Scenarios were constructed to reflect maximum potential market acceptance and penetration rates to determine whether the 2050 GHG goals are possible and to quantify the corresponding increase/decrease in fuel and vehicle costs. The scenarios assess the economic and GHG tradeoffs between electrification of the fleet and improvement of existing ICE technologies. This report presents the results as follows:

- Section 2 describes the analysis methodology and presents key analysis assumptions
- Section 3 provides BAU projections for the California and U.S. analyses
- Section 4 provides 2050 emissions and costs on a per mile basis for a wide range of vehicle technology and fuel combinations
- Section 5 provides results for the U.S. scenario analysis
- Section 6 provides the California scenario analysis results
- Section 7 summarizes the conclusions drawn from the results
- Appendix A provides support for fuel economy and incremental cost projections utilized
- Appendix B provides details on the well-to-wheels CI values used in the U.S. analysis
- Appendix C describes the well-to-wheels CI values used in the California analysis
- Appendix D and Appendix E describe the new vehicle market share projections for each of the compliance scenarios in the U.S. and California Analyses, respectively.

[20] HEV technology is acceptable in light duty trucks used as passenger vehicles like SUVs that are not used for towing provided consumer range and costs expectations are met.

2. Methodology and Analysis Assumptions

As discussed above, this study projects annual GHG emissions from the U.S. and California light-duty transportation fleets. A business-as-usual (BAU) case was defined to estimate annual GHG emissions through 2050 assuming no new fuel economy standards or regulations are adopted (except that NHTSA finalizes the augural fuel economy standards for 2022-2025). This BAU case is subsequently compared to a range of scenarios that attempt to achieve the 2050 GHG targets. This section describes the modeling methodology and the process of developing realistic assumptions for key model inputs to generate the BAU results.

2.1 Methodology

To generate projections of fuel consumption, fuel spending and vehicle spending, a vehicle stock model is used as illustrated schematically in Figure 2-1. The main feature of the model is tracking the number of vehicles by model year (MY) and technology type on the road each year. This is accomplished by specifying the total light auto and light truck sales each year, splitting the sales between different technology types (e.g. ICE gasoline, HEV, BEV, etc.), and then applying an assumed survival rate profile so that fewer vehicles of a given MY remain after each calendar year. Note that for this first critical input, vehicle sales and survival rates must be modeled at least 25 years prior to the first analysis year (2016 in this case) to initiate the assessment with a realistic spread of model years in the current on-road vehicle population.

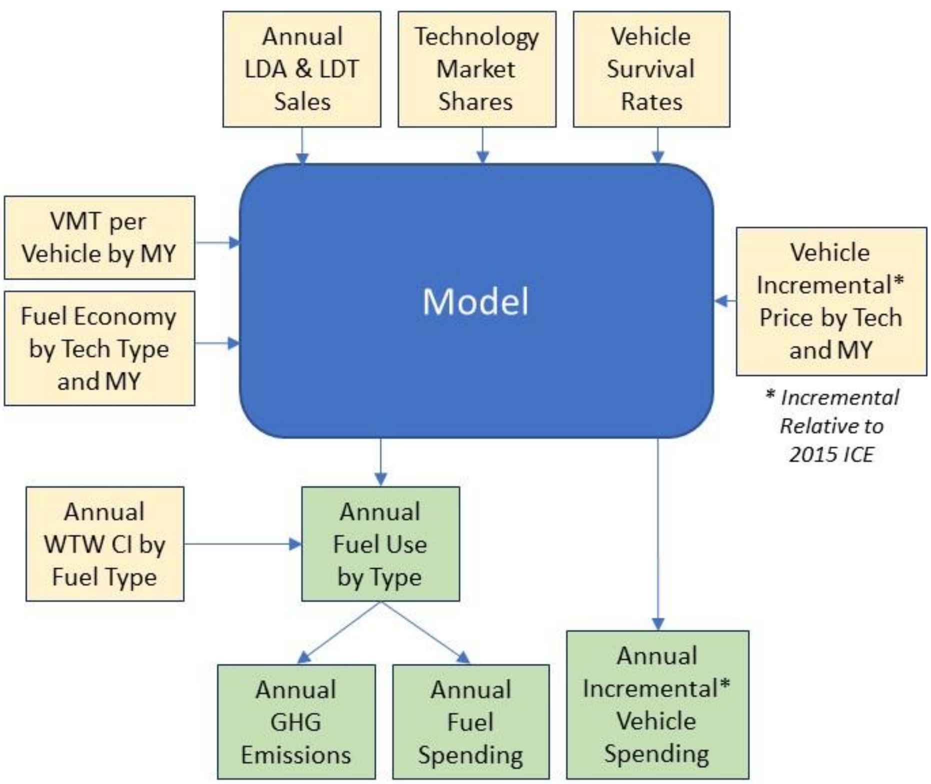

Figure 2-1. Schematic illustrating the modeling methodology

The second key assumption in the model is the average on road fuel economy for each vehicle technology type over the analysis period. Since fuel economy standards change over time, each model year and technology have an average on road fuel economy value assigned to it.[21] Each calendar year, a population weighted average fuel economy is calculated for each technology. For example, to calculate the average light auto ICE fuel economy in 2020, the number of MY2020 ICE vehicles is multiplied by the MY2020 fuel economy and added to the number of MY2019 vehicles multiplied by the MY2019 fuel economy and so on. The sum of these products is then divided by the total number of vehicles in calendar year 2020 to arrive at the weighted average fuel economy for light auto ICEs in 2020. This calculation is performed for each calendar year from 2016-2050 and each vehicle technology type.

The third key input is the average vehicle miles traveled (VMT) per vehicle. Like fuel economy, this factor varies by vehicle application and age with light duty trucks traveling more than light duty autos and new vehicles traveling more miles than older vehicles. Using these inputs, the number of vehicles can be combined with the average fuel economy and average per vehicle VMT to yield total annual fuel consumption (by fuel type) for the analysis period.

To quantify annual fuel consumption, Argonne National Laboratory's VISION2015 model was utilized as the starting point for the U.S. light fleet analysis. Each year, Argonne updates the VISION model with the Department of Energy's Annual Energy Outlook (AEO) projections for vehicle sales, technology market shares, VMT, and fuel economy. The VISION2015 model is populated with AEO2015 data. LCA updated VISION2015 with data from AEO2016 and other sources as described later in this section and in the Appendices. For the California analysis, the California Air Resources Board (ARB) VISION model[22] provided the starting point. The U.S. and California VISION models divide the light-duty sector into light-duty autos (LDAs) and light-duty trucks (LDTs). Light trucks include vehicles up to 8500 lbs[23] (Class 2b trucks are not included).

For this analysis, LCA added three features to the basic VISION modeling framework. First, LCA developed and added CI factors for each fuel/feedstock combination to quantify annual GHG emissions from the LDA and LDT fleets. U.S. average factors were used in the U.S. model and California specific factors were used in the California model. Second, profiles of incremental vehicle cost relative to a 2015 ICE vehicle were established for each technology based on projections by EPA, NHTSA, ARB, NAS and others. The incremental cost profiles were applied to annual vehicle sales to determine annual incremental vehicle costs relative to a 2015 ICE. Finally, LCA added fuel cost profiles to quantify fuel spending over the analysis period.

[21] On road fuel economy is determined from fuel economy standards and factored down based on vehicle technology type, i.e. ICE gasoline, HEV, or BEV. See Section 2.5 for conversion to on-road fuel economy.
[22] VISION 2.1 Passenger Fleet Module https://www.arb.ca.gov/planning/vision/downloads.htm#2016vision21lr *The ARB model is a Microsoft Access database file. The data for light-duty vehicles was extracted and LCA constructed a Microsoft Excel version of the model consistent with the structure of the U.S. VISION model.*
[23] Class 1 and Class 2a for the federal analysis and LDT1, LDT2, MDV for the California analysis.

The following sections step through the underlying assumptions used to develop the U.S. and California BAU forecasts.

2.2 BAU Vehicle Sales Forecast

Projections of annual vehicle sales are critical to accurate projections of fuel consumption and GHG emissions. For the U.S. analysis, the VISION2015 model was modified by replacing the vehicle sales projections with those in AEO2016. Figure 2-2 provides the default VISION (AEO2015)[24] vehicle sales and the AEO2016 sales (dashed lines). Note that a short-term increase in light truck sales is anticipated followed by a gradual increase in light auto sales relative to light truck sales for 2020-2050. Total light-duty sales are not projected to re-attain the peak achieved in 2000 (17,350,000 vehicles) until 2048. Vehicle sales responded to many important economic events including the recession after the 9/11 attacks, the 2008 economic crisis, and the decrease in oil prices which started in 2014. AEO2016 projections extend through 2040; for the analysis, the 2041-2050 LDA and LDT sales are assumed to continue linearly along their respective VISION2015 slopes.

For the California analysis, vehicle sales projections are taken directly from ARB's VISION model. Figure 2-3 provides the light auto and light truck historic and projected sales. It is interesting to note that in contrast to national sales, light autos sales have recovered more strongly than light trucks in California and are predicted to approximately double light truck sales for 2020-2050. In addition, California has recently been near pre-recession sales volumes.

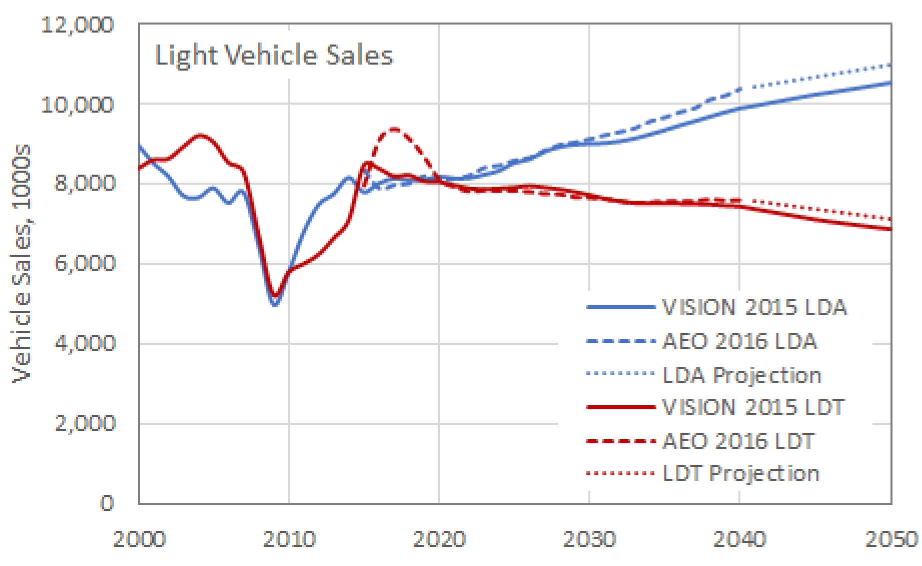

Figure 2-2. Historic and projected U.S. light-duty vehicle sales

[24] The DOE Energy Information Administration Annual Energy Outlook reference case with Clean Power Plan.

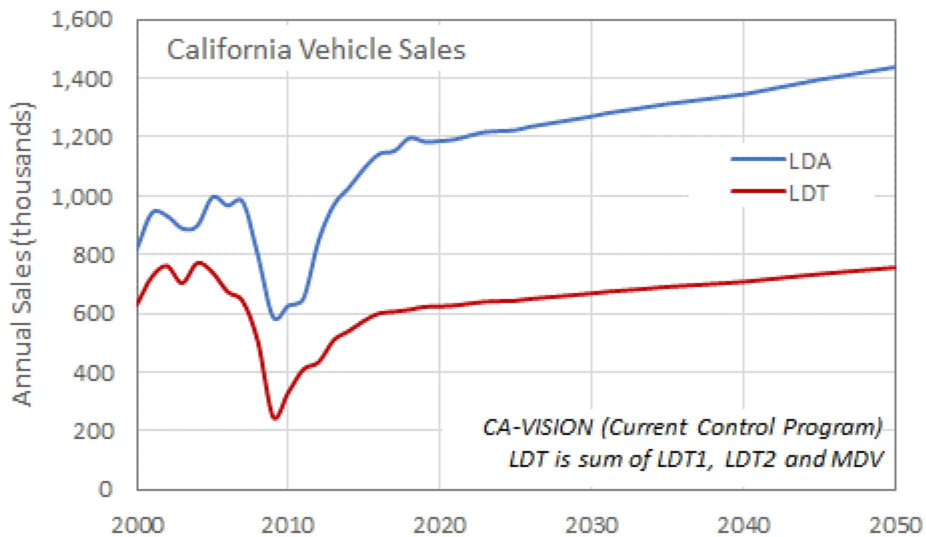

Figure 2-3. Historic and projected California light-duty vehicle sales

2.3 BAU New Vehicle Technology Market Shares

The other key assumption for vehicle populations is technology market share. Specifically, annual projections for the share of new LDAs and LDTs sold each year that are gasoline ICE, diesel, FFV, HEV, PHEV, BEV, or FCV. Figure 2-4 provides historic and projected new LDA vehicle technology market shares for the BAU U.S. market. The market share values for 2016 and later are taken from AEO2016 with three exceptions. First, AEO2016 projects that LDA diesel shares steadily increase to 6% by 2023. In contrast, the recent EPA Midterm Evaluation[25] assumes diesel vehicles will have 0.9% market share in 2025. Considering issues with Volkswagen's emission controls, and because Volkswagen represented the majority of LDA diesel vehicles sold, this analysis assumes 0.9% for LDA diesel new vehicle market share.

Second, the AEO2016 projection for HEVs increases from 4.6% in 2016 to 6.6% in 2025 and then continues to grow linearly to over 8% by 2040. In contrast, the EPA Midterm Evaluation (MTE) projects a market share of 4.5% by 2025. For this analysis, a midpoint value of 5.5% in 2025 is used. Although the MTE suggests that ICE technologies will be able to meet the 2025 standards without use of hybridization (no growth in HEV shares[26]), HEVs may pick up some of the lost diesel sales. Rather than the linear increase in AEO2016, this analysis maintains a steady HEV market share from 2025-2050, consistent with the MTE forecast. Because the current CAFE standard ends in 2025, there is no reason for shares to increase after 2025.

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[25] EPA, NHTSA, CARB Technical Assessment Report, Midterm Evaluation of Light-Duty Vehicle GHG Emissions Standards for Model Years 2022-2025, July 2016.

[26] HEV used in this report refers to full or strong hybrid electric vehicles as compared to mild hybrids with 12- or 48-volt integrated belt starter generator (IBSG) systems.

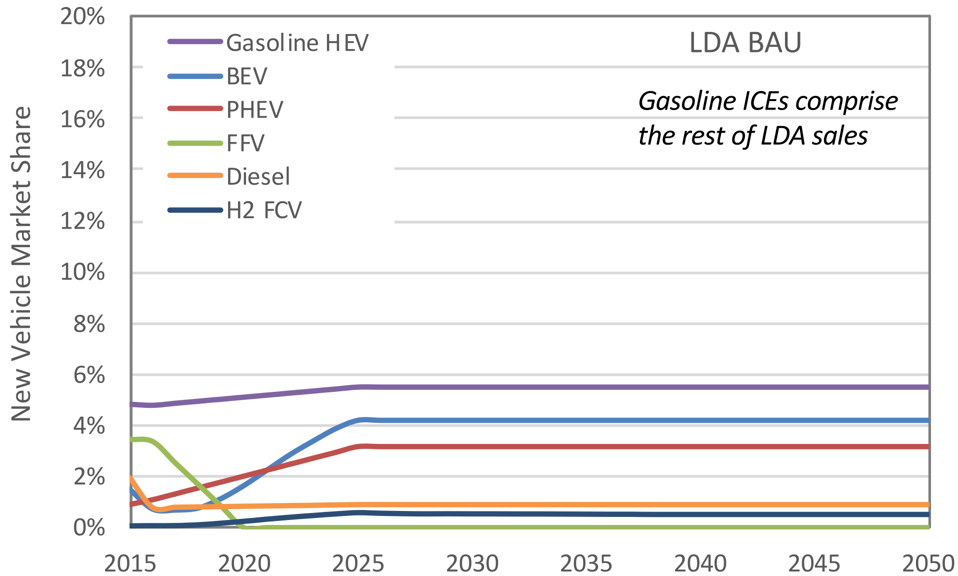

Figure 2-4. Projected U.S. LDA alternative fuel technology market shares

Finally, the AEO2016 projection for FFVs decreases slightly from 3.4% in 2016 to 2.6% in 2025 and is constant thereafter. For many years, auto manufacturers have received a significant CAFE credit for each FFV sold. Beginning in 2017, CAFE credits will be granted depending upon how much E85 those vehicles consume. At present, it isn't feasible to track E85 use, so there is no incentive for manufacturers to continue providing FFVs, even though the additional cost is low. For this reason, the U.S. BAU FFV market share profile has been reshaped with a linear decrease from 2016 levels to 0% by 2020.

The EPA MTE values for BEVs and PHEVs through 2025 agree well with the AEO2016 projections. The MTE does not include a value for hydrogen FCVs, so the AEO2016 forecast is utilized. AEO2016 also divides the BEV category into BEVs with 100-mile range and BEVs with 200-mile range. For 2015, AEO2016 states that the BEV100/BEV200 split was 63/37 and projects that the BEV100/BEV200 split by 2025 will be 40/60. Strangely, the AEO BEV100/BEV200 split for 2040 reverses trend and increases to 57/43. LCA disagrees with the 2040 forecast and believes that the 2015-2025 trend of more BEV200 models will continue through the end of the analysis period due to continuous improvement in battery technology. This analysis retains the AEO2016 splits for 2015 and 2025 and assumes that BEV200 penetration will continue to increase but level off near 2050. The BEV200 market shares utilized here are 37% in 2015, 60% in 2025 to 85% in 2050. The corresponding BEV100 penetrations are 63% in 2015, 40% in 2025, and 15% in 2050.

Figure 2-5 shows the resulting BAU light-duty auto vehicle stock by technology historically and assumed future vehicle populations. The downward aberration reflects the decrease in vehicle stock after the 2008 economic crisis and subsequent slow rise back to pre-crisis levels. Gasoline ICE vehicles remain dominant through 2050. The FFV population is expected to dwindle by 2035 without the CAFE credit.

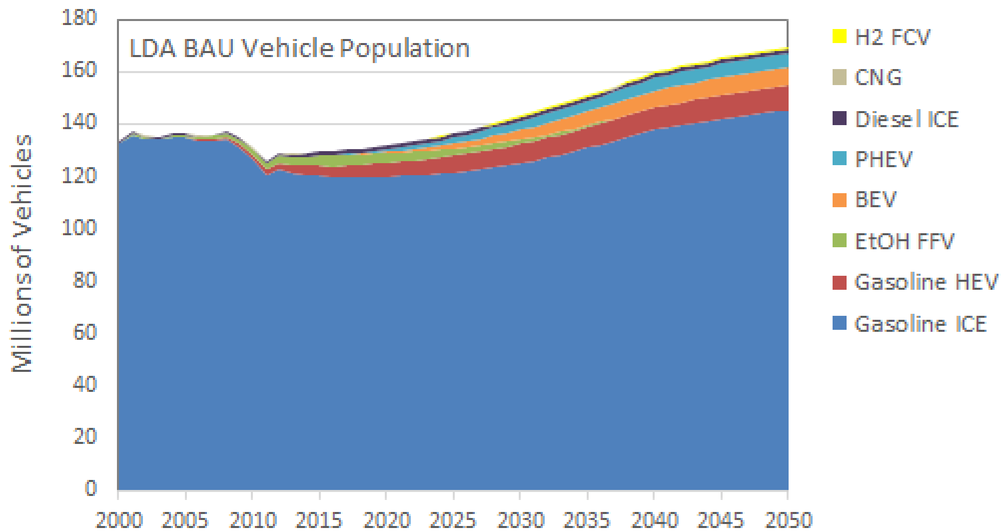

Figure 2-5. Projected U.S. LDA population by technology type for BAU

The light truck market share values used for the U.S. BAU case are shown in Figure 2-6. For diesels, AEO2016 assumes an increase from 1.4% in 2015 to 2% in 2025 and remaining constant thereafter. VISION2015 assumes 0.6% in 2015 increasing to 1.9% in 2025 and decreasing back down to 1.6% in 2040. The 2025 EPA MTE estimate is 1%. An intermediate value of 1.5% is used in 2025 with shares remaining constant for the remainder of the analysis period.

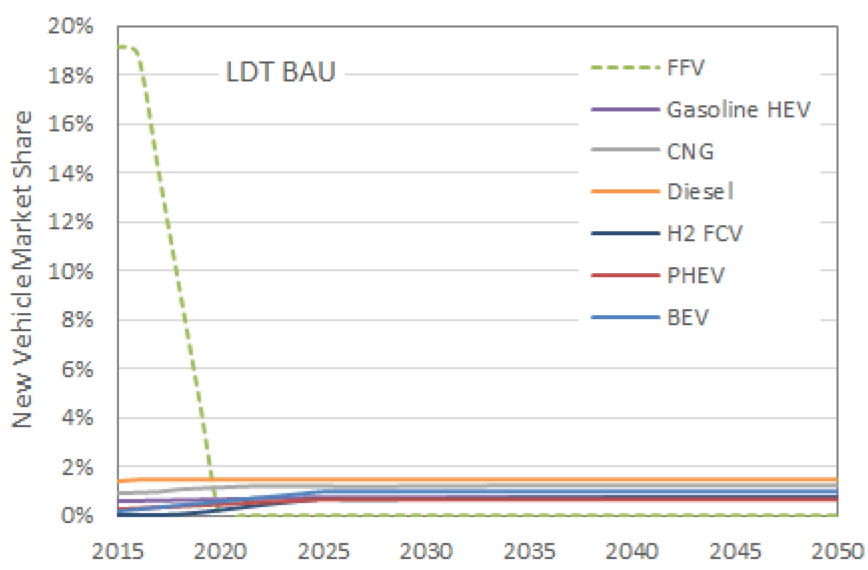

Figure 2-6. Projected BAU U.S. LDT technology market shares

For light truck HEVs, VISION2015 forecasts an increase from 0.3% in 2015 to 0.6% in 2025 and increasing gradually to 0.8% by 2050. The AEO2016 forecast begins at 0.6% in 2015 and increases to 1.1% in 2025 and gradually increasing to 1.4% by 2050. The EPA MTE 2025 estimate is 0.5% market share. An intermediate value of 0.75% is assumed for 2025 with no increase beyond due to the current lack of CAFE requirements.

For light truck BEVs, AEO2016 projects an increase in market share from 0.1% in 2015 to 1.5% in 2025 and holding constant at 1.5% through the end of the analysis period. The EPA MTE forecasts 0.4% by 2025. This analysis assumes a linear increase to an intermediate value of 1% by 2025 and constant thereafter. The AEO2016 BEV100/BEV200 split is used here: 60/40 in 2015, gradually decreasing to 50/50 by 2025 and remaining there through 2050. For light truck PHEVs, AEO2016 projects an increase in market share from 0.2% in 2015 to 0.9% in 2025; whereas, the MTE forecasts 0.5% by 2025. For this analysis, we assume a linear increase to the intermediate value of 0.7% in 2025 and constant through the end of the analysis period.

EPA does not provide a forecast for FFVs, but the AEO2016 projection assumes a 17% market share for the entire analysis period. Because of the change in the FFV CAFE credit for MY 2017 and later, this analysis assumes that FFV market share decreases linearly to 0% by 2020. The near-term decrease is reflected in the decline of FFV models from 167 in 2015/2016 to 133 in 2016/2017[27].

In the absence of EPA MTE projections for CNG vehicles and hydrogen FCVs, the AEO2016 projections are utilized. Figure 2-7 provides the U.S. BAU light truck populations calculated by the VISION model based on the assumed new truck market share values shown in Figure 2-6.

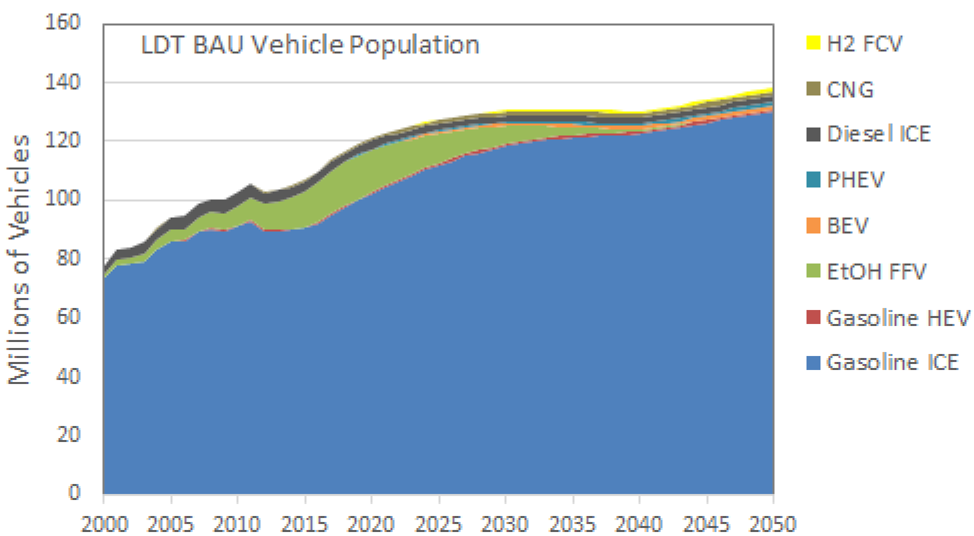

Figure 2-7. Projected U.S. LDT population by technology type for BAU

For the California fleet, the default ARB market share values were utilized. However, ARB groups CNG vehicles, FFVs and HEVs in the gasoline ICE category. An HEV category was created by using the average ratio of 2007-2009 California HEV sales to U.S. Sales[28]. This ratio was applied to the U.S. HEV market share forecasts for LDA and LDT through 2050 to approximate the California market shares. Because California consumes negligible amounts of E85, a

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[27] www.fueleconomy.gov

[28] The ratio is 2.4. California specific HEV sales data were not available for more recent years.

separate FFV category was not created for the California BAU. Additionally, the BEV category does not distinguish between BEV100 and BEV200 so this analysis utilized the same split assumed for the U.S. fleet. The BEV and PHEV market shares are based on California's Zero Emission Vehicle (ZEV) regulation. Figure 2-8 summarizes LDA market shares and Figure 2-9 provides the LDA stock by technology type for the California BAU case.

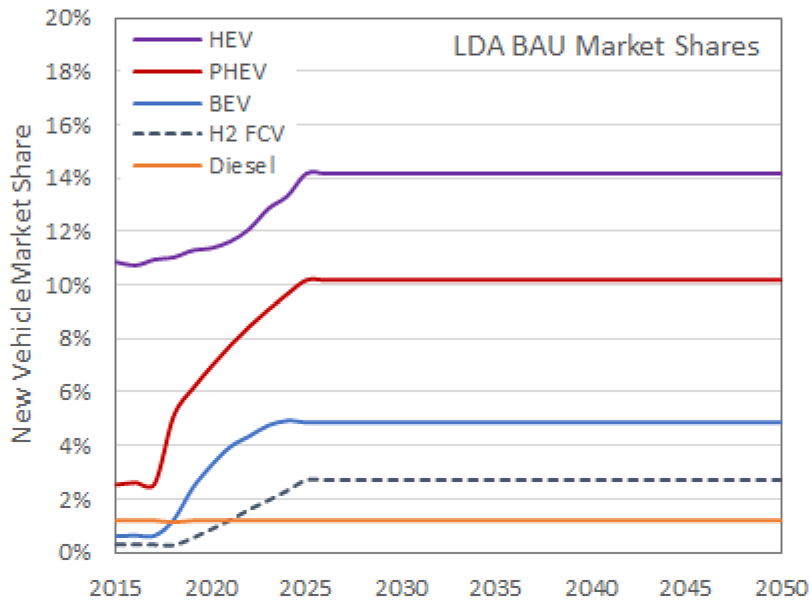

Figure 2-8. Projected California LDA Technology Market Shares

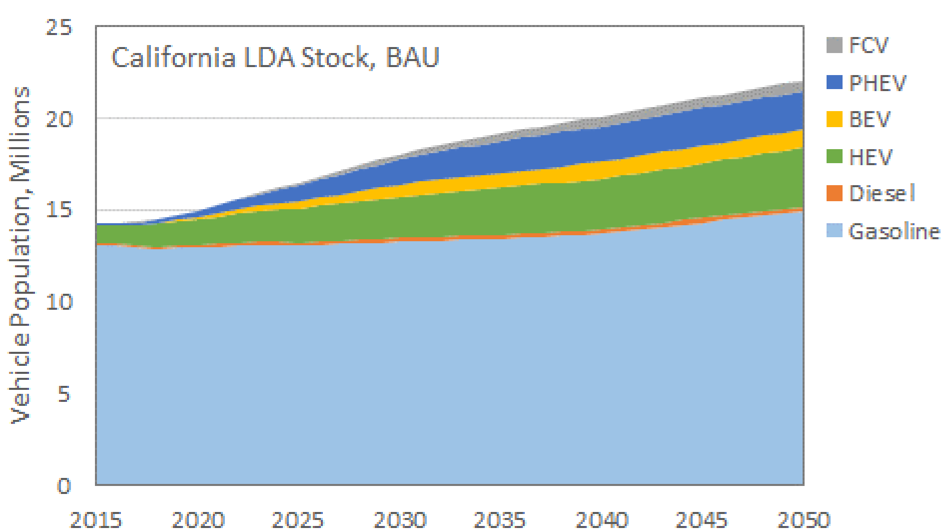

Figure 2-9. Projected California LDA stock by technology type for BAU

For California LDTs, a CNG category was created by assuming the same market share as the U.S. analysis and taking them from the gasoline ICE share. As with LDAs, ARB does not divide BEVs into BEV100 and BEV200 categories. Figure 2-10 illustrates the assumed LDT BAU market shares for California while Figure 2-11 provides the resulting vehicle population by technology type. Note that the California market share forecasts for BEVs, PHEVs, and FCVs are higher than the U.S. values due to the ZEV Mandate.

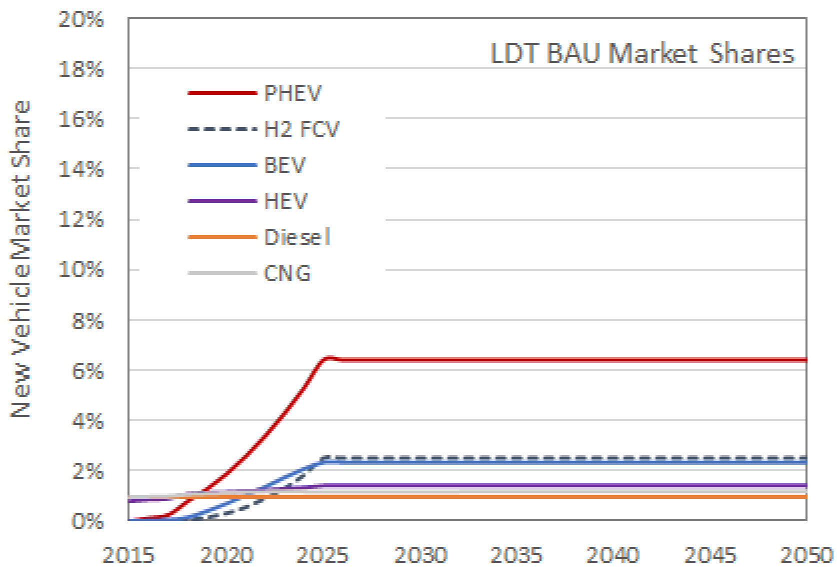

Figure 2-10. Projected California LDT technology market shares

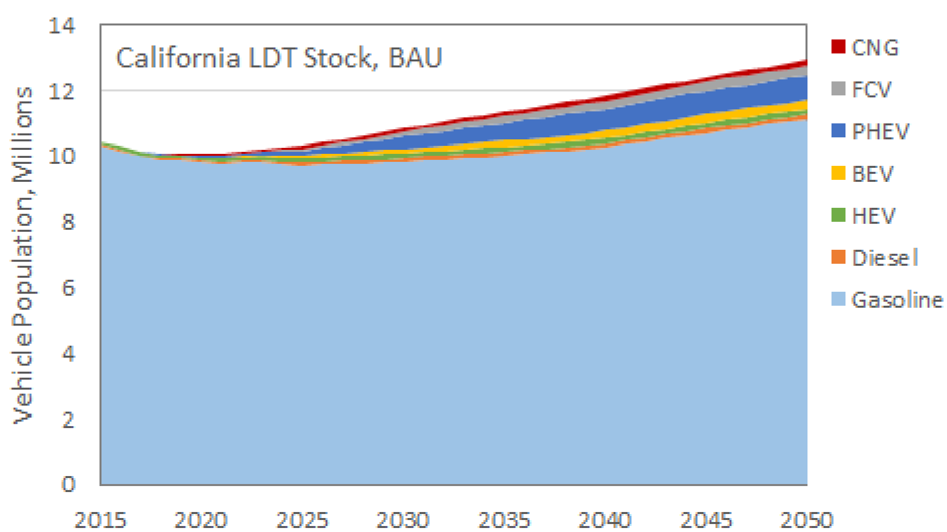

Figure 2-11. Projected California light truck stock by technology type for BAU

2.4 BAU Vehicle Miles Traveled

Another key input to quantify fuel use is vehicle miles travelled (VMT). Figure 2-12 shows the projected U.S. average LDA and LDT per vehicle VMT. AEO2015 (data used in VISION2015) projects only through 2040; Argonne extrapolated the forecasts through 2050. Unfortunately, AEO2016 does not provide separate forecasts for LDA and LDT, but it is evident that the profiles are different. AEO2015 assumes a steady increase in VMT while AEO2016 assumes a near-term increase (likely based on low petroleum prices) followed by slower growth. This analysis uses the more recent AEO2016 profile but separates it into LDA and LDT components by using the AEO2015 VMT per vehicle forecasts for LDA and LDT and their relative proportion of the vehicle population, as indicated by the red and blue dotted lines.

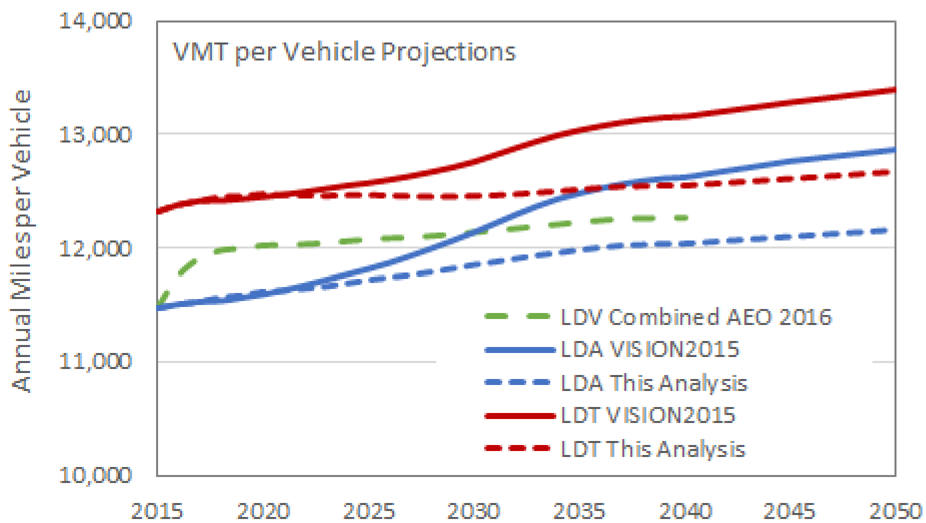

Figure 2-12. Projected U.S. Average VMT per vehicle for light-duty autos and trucks

For the California analysis, VMT data were extracted from CA-VISION. Different vehicle technologies and model years have different annual VMT. The weighted average VMT values are provided in Figure 2-13. It is interesting to note that the U.S. analysis assumes that LDTs have higher annual VMT than LDAs while in California the opposite is true. Moreover, while the U.S. is projected to have slightly increasing VMT through 2050, the VMT in California is projected to decrease significantly, presumably due to provisions of SB 375[29].

[29] The Sustainable Communities and Climate Protection Act of 2008

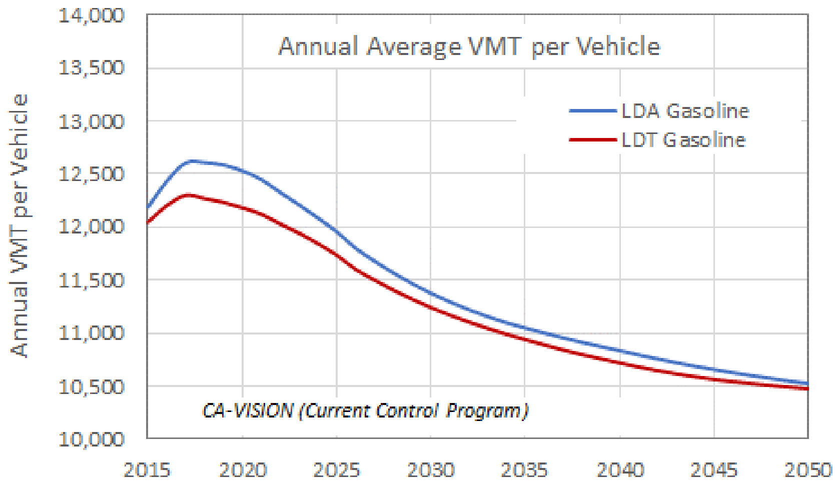

Figure 2-13. Projected California average LDA and LDT VMT

2.5 Fuel Economy Forecasts

Projected vehicle fuel economy for the range of vehicle technologies evaluated is a key input to this analysis. Several studies informed the development of fuel economy values and incremental costs. These include:

- Energy Information Administration Annual Energy Outlook 2016 (AEO2016)
- VISION2015 Default Values (same as AEO2015)
- NAS Transitions Report[30]
- Argonne C2G Analysis[31]
- Draft MTE (EPA and NHTSA did separate analyses)[32]
- EPA Fuel Economy Guide[33]
- ARB[34]

As discussed above, the VISION model divides the light-duty transportation sector into two categories: autos and light trucks. The model uses a composite fuel economy for new vehicles in each category based on a sales-weighted average (based on AEO sales projections) of corporate average fuel economy (CAFE) certification values by sub-class. To better reflect real-world fuel economy, the certification fuel economy is then degraded to reflect on-road performance in VISION. Degradation factors are established by the EIA: [35] 0.817 for gasoline, diesel, FFV, CNG and PHEV ICE operation, 0.85 for HEV and hydrogen FCVs, and 0.70 for EVs.

[30] Transitions to Alternative Vehicles and Fuels, National Research Council of the National Academies, 2013.
[31] Cradle-to-Grave Lifecycle Analysis of U.S. Light-duty Vehicle Fuel Pathways: A GHG Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies, Argonne National Laboratory, June 2016
[32] Draft Technical Assessment Report: Midterm Evaluation of Light-duty GHG Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025, U.S. Environmental Protection Agency, California Air Resources Board, National Highway Traffic Safety Administration, EPA-420-D-16-900, July 2016.
[33] www.fueleconomy.gov
[34] California Air Resources Board projection based on EMFAC and VISION2.1 fuel consumption and VMT projections
[35] Conversation with Yan Zhou, Argonne National Laboratory

Figure 2-14 and Figure 2-15 show the LDA and LDT fuel economy values utilized in this analysis, which were established based on the studies listed above. Appendix A provides a detailed technology by technology comparison of the estimates from these studies. Fuel economy values shown below are non-degraded CAFE certification values, which were subsequently degraded in VISION for this analysis.

These fuel economy values were utilized for both the U.S. and California analyses with one exception. The California analysis uses the on-road fuel economy values for gasoline and diesel vehicles back-calculated from CA-VISION2.1 fuel consumption and VMT values. These values are close to the U.S. analysis values and may also be found in Appendix A. In addition, the fuel economy for California's consolidated BEV category in this analysis is a market share weighted average of the BEV100 and BEV200 fuel economy values.

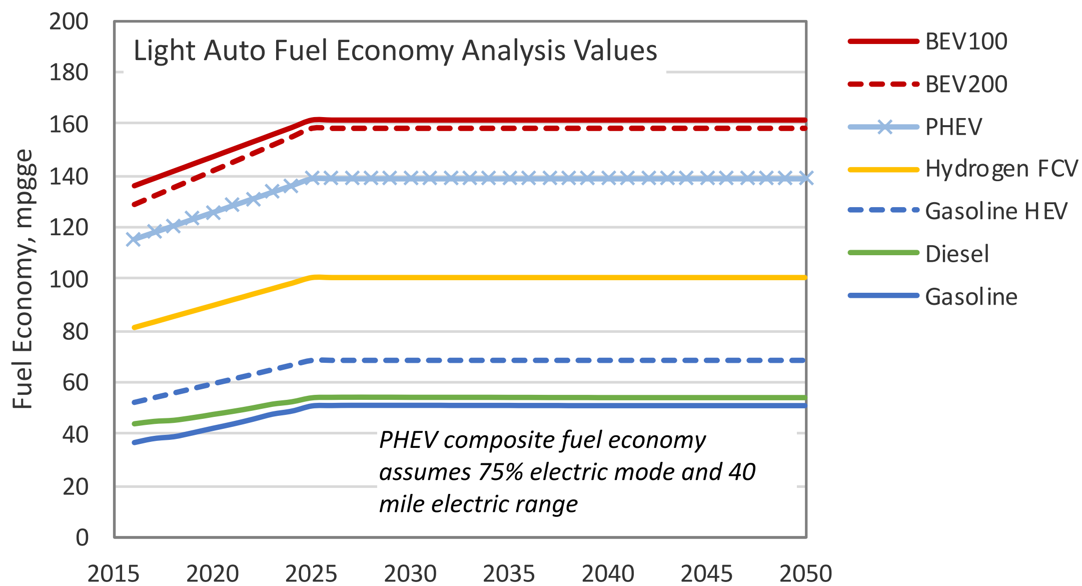

Figure 2-14. Summary of light auto certification composite fuel economy values (BAU)

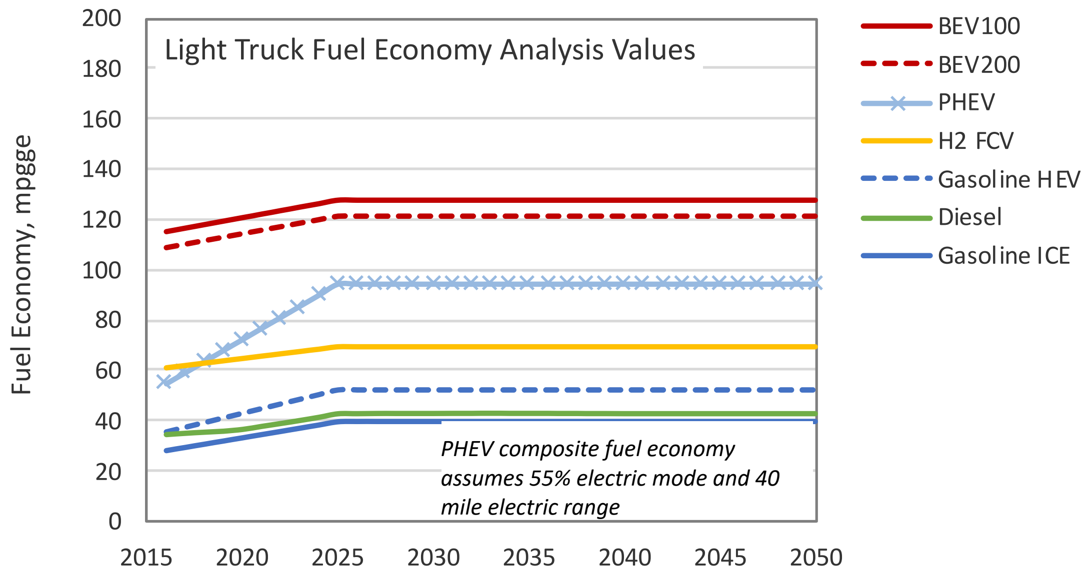

Figure 2-15. Summary of light truck certification composite fuel economy values (BAU)

As indicated in the figures, the BAU case assumes no further improvement in fuel economy after 2025 because CAFE standards have not been established for subsequent years. However, we have also included a BAU scenario where vehicle technology improves due to manufacturing improvements associated with incremental technology advancement as experience with these technologies continues and with improvements associated with increased production volumes (referred to as BAU with fuel economy improvements post 2025). To give us some guidelines as to the possible improvement of each technology, the change in fuel economy and MSRP for the Toyota Prius was considered (Figure 2-16). Fuel economy improved 1.7% per year from 2001 to 2017 while the MSRP declined by 0.6% per year. These data provide the basis for assumptions of continued fuel economy improvement 2026-2050 in the GHG reduction scenarios. Gasoline ICEs which are more fully developed are assumed to improve by 0.5% per year, whereas the electric technologies which are less developed are projected to improve more--HEVs by 1% per year and electric drive vehicles by 1.5% per year. It is further assumed that there is no increase in incremental cost associated with these improvements.

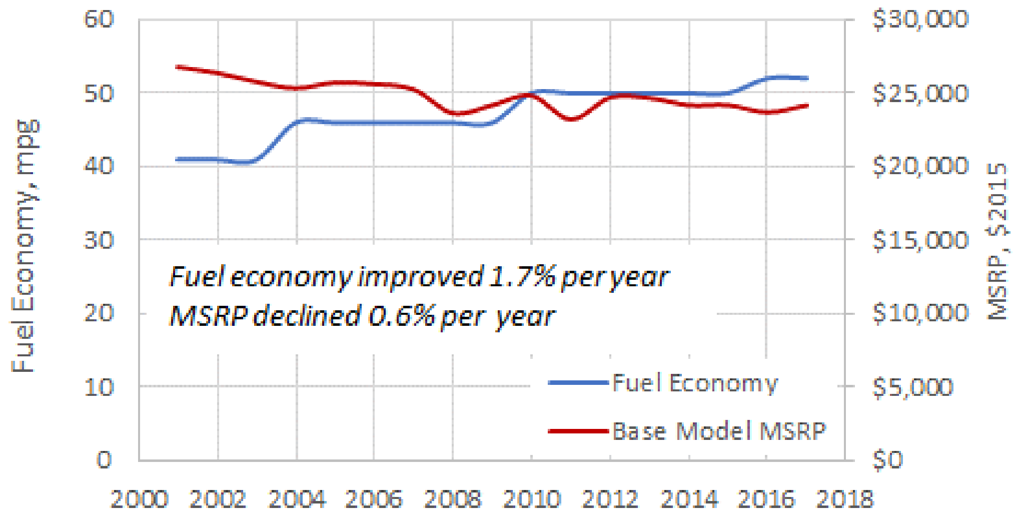

Figure 2-16. Change in Toyota Prius fuel economy and MSRP

Although not included in the BAU case, vehicles with engines designed to operate on high octane fuels (HOF) such as E30 with a research octane number (RON) of 100 and E70/E85 with a RON of 103 were included as candidates for the GHG reduction scenarios. Note that in addition to ICEs, HEVs and PHEVs can also be dedicated HOF vehicles. The Dedicated High Octane Fuel (HOF) Vehicles section of Appendix A contains a detailed discussion of the fuel economy benefits assigned to HOF vehicles in this analysis.

Table 2-1 summarizes the certification fuel economy values and corresponding energy economy ratios (EERs) used in this analysis. EERs are the ratio of advanced technology fuel economy to gasoline ICE fuel economy at a given timeframe and express the fuel economy improvement of the advanced technology. For example, in 2015 BEV100 vehicles fuel economy is 3.71 greater than gasoline ICE vehicle fuel economy. For BAU, fuel economy does not improve beyond 2025 because the current CAFE standards do not extend beyond 2025, so values used in 2050 are the same as 2025. The 2050 values shown in the table were used in the BAU with fuel economy improvement and in the GHG reduction scenarios.

For the LDA category, most of the studies had fuel economy estimates that agreed with each other. However, there is a fair amount of spread on BEV100 fuel economy. The analysis values selected for LDA BEV100 may be slightly low. A sensitivity analysis (presented in Section 5.7) addresses this uncertainty; for this analysis the BEV100 fuel economy was increased to 172 mpgge (from the base case 162 mpgge), based on the Argonne C2G/AEO2016 2025 estimate. Because the BEV200 fuel economy forecast is based on the BEV100 forecast, the BEV200 fuel economy is also increased in the sensitivity test case.

For LDTs, there is uncertainty around future fuel economy estimates of BEVs and PHEVs operating in electric mode. However, the ratio of LDT to LDA fuel economy for BEVs is consistent with that of gasoline ICEVs, so the values utilized appear reasonable. It would be valuable if Argonne expanded their recent C2G study to also include LDTs.

Table 2-1. Summary of certification fuel economy and EER analysis values

Certification Fuel Economy in mpgge	Light Duty Auto						Light Duty Truck					
	Fuel Economy			EER			Fuel Economy			EER		
	2016	2025	2050	2016	2025	2050	2016	2025	2050	2016	2025	2050
Gasoline ICE	37	51	58	1.00	1.00	1.00	28	40	45	1.00	1.00	1.00
Diesel	44	54	62	1.21	1.06	1.06	34	42	48	1.21	1.07	1.07
FFV-Gasoline Mode	37	51	58	1.00	1.00	1.00	28	40	45	1.00	1.00	1.00
FFV-EtOH Mode	38	53	60	1.03	1.03	1.03	29	41	46	1.03	1.03	1.03
Gasoline HEV	52	69	83	1.42	1.35	1.43	36	53	64	1.28	1.33	1.41
PHEV-Gasoline Mode	52	69	83	1.42	1.35	1.43	36	53	64	1.28	1.33	1.41
PHEV-Electric Mode	136	162	221	3.71	3.16	3.80	70	128	175	2.48	3.22	3.88
BEV-100	136	162	221	3.71	3.16	3.80	115	128	175	4.08	3.22	3.88
BEV-200	129	158	216	3.53	3.09	3.72	109	121	166	3.87	3.06	3.68
Hydrogen FCV	81	101	138	2.22	1.97	2.37	61	69	94	2.16	1.74	2.10
E30 ICE (RON 100)	39	54	61	1.06	1.06	1.06	29.8	41.9	47.5	1.06	1.06	1.06
E30 HEV (RON 100)	55	73	88	1.49	1.42	1.51	38.0	55.7	67.1	1.35	1.40	1.49
E70 ICE (RON 103)	40	56	63	1.08	1.08	1.08	30.6	43.1	48.8	1.08	1.08	1.08
E70 HEV (RON 103)	56	75	90	1.53	1.46	1.55	39.0	57.2	69.0	1.38	1.44	1.53
2050 values shown assume continuing technology improvement to meet tighter CAFE standards for 2026-2050.												

2.6 Fuel Blend Assumptions

Projected light-duty fuel consumption is computed from vehicle population, fuel economy and VMT projections. Several fuels are blends of different feedstocks and several vehicles can use more than one fuel. For example, gasoline is currently a blend of denatured ethanol and gasoline blendstock. Diesel contains a certain amount of biodiesel and renewable diesel. CNG is a blend of renewable natural gas (RNG) and fossil natural gas. The following assumptions are made about fuels for the BAU and GHG reduction scenarios.

- Current motor gasoline contains on average 9.8% by volume denatured ethanol.[36] This blend level is utilized for 2016 and then increased to 10% for 2017 and beyond.
- Denatured ethanol is assumed to contain 2% by volume gasoline blendstock (E10 contains 10% by volume denatured ethanol, so slightly less than 10% neat ethanol)
- FFVs can consume gasoline (E10) or a high-level ethanol blend. The AEO2016 reference case[37] sets current FFVs using E85 fuel at 4.5% of the time, growing to 17% by 2040. However, as discussed above, AEO2016 also projects increasing sales of FFVs despite expiration of the FFV CAFE credit. This analysis quickly phases out FFV sales (see above) and sets 2016 FFV E85 fuel use at 4.5%, maintaining it there through 2050.
- High level ethanol blends are assumed to be 70% ethanol (E70) for the BAU and 85% ethanol (E85) for the GHG reduction scenarios.

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[36] EIA 2015 fuel ethanol and motor gasoline consumption

[37] Based on AEO2016 projections of ethanol use in high level blends and VISION FFV projected fuel consumption

- PHEVs consume both electricity and gasoline; one key assumption is the share of operation in electric mode vs gasoline mode. This depends on battery size. This analysis assumes that future PHEVs will have a 40-mile range or more and that PHEVs with 10-mile range are being phased out[38]. Based on EV Project[39] data for the Chevy Volt (40-mile range), 74.5% of LDA miles driven are electric miles. The Dodge Ram PHEV portion of the report indicates that LDT E_{VMT} is between 22% and 46%. However, the authors state that Ram drivers were not enthusiastic about maximizing E_{VMT} and these fleet vehicles were not placed into operation that allowed charging. Less than 5% of light trucks are sold into fleets and it is expected that most SUVs would be operated like LDAs. For this analysis, we use an intermediate value of 55% for LDT E_{VMT}.
- U.S. cellulosic ethanol volumes are assumed to consist entirely of volumes consumed in the two LCFS states (California and Oregon). ARB's most recent compliance forecast[40] is utilized for BAU cellulosic, sugarcane and corn/sorghum/wheat volumes. ARB forecasts 400 MGY of cellulosic ethanol by 2025. The volumes are increased by 3% since Oregon's on-road gasoline consumption is approximately 3% of California's.
- Figure 2-17 provides the AEO2016 projected biodiesel (BD) and renewable diesel (RD) blend levels. Although most of the diesel fuel is consumed by the heavy-duty fleet, it is assumed that the light-duty and heavy-duty fleet all use the same biodiesel and renewable diesel blend levels.
- Four different feedstocks are considered for biodiesel and renewable diesel: soybean, canola, corn oil, and UCO/tallow. A recent UCS-ICCT sponsored study[41] found that in 2014, the shares of biodiesel produced from these feedstocks were 53% soybean, 25% tallow/UCO, 12% canola, and 11% corn. These feedstock shares were used in this analysis through 2050 for biodiesel and renewable diesel.
- The RNG share of CNG is based on ARB's projected California RNG use through 2025 divided by total on-road U.S. CNG consumption projected by VISION (Figure 2-18). For the BAU case, the ARB forecast is extended linearly to 2050. In the max RNG scenario, it is assumed that production follows CNG, reaching 80% of total by 2050. The projected volume, 4 BGY (diesel equivalent) is well within commercial potential of ~ 18 BGY[42] according to the American Gas Foundation, but much higher than the 0.6 BGY thought to be commercially viable at today's RIN and LCFS credit prices by UC Davis researchers[43].

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[38] Conversation with Eileen Tutt, CalETC

[39] *Plug-in Electric Vehicle and Infrastructure Analysis (Chapter 11)*, Idaho National Laboratory, September 2015.

[40] ARB LCFS Illustrative Compliance Scenario, 4-1-2015

[41] "Projections of U.S. Production of Biodiesel Feedstock", Wade Brorson for Union of Concerned Scientists and International Council on Clean Transportation, July 2015.

[42] The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality, American Gas Foundation, Sept 2011.

[43] ARB Contract No. 13-307, The Feasibility of Renewable Natural Gas as a Large-Scale, Low-Carbon Substitute, Draft Final Report, June 2016, Amy Myers Jaffe, UC Davis ITS.

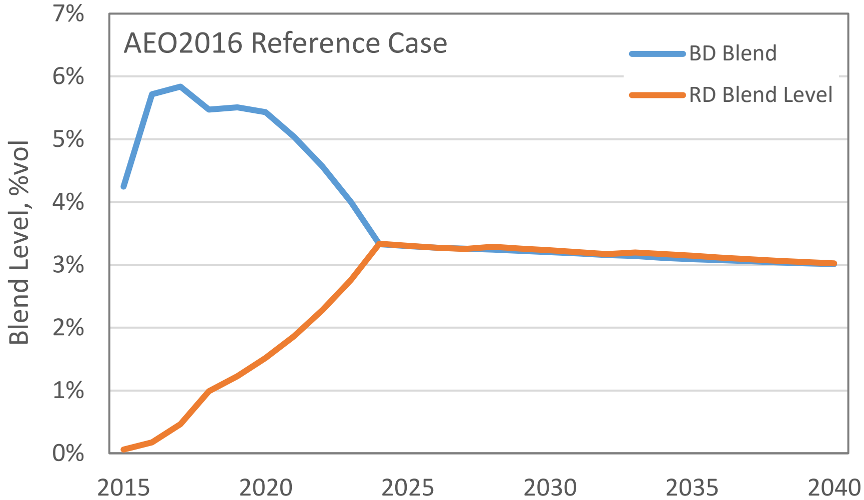


Figure 2-17. AEO2016 projected RD and BD blend levels

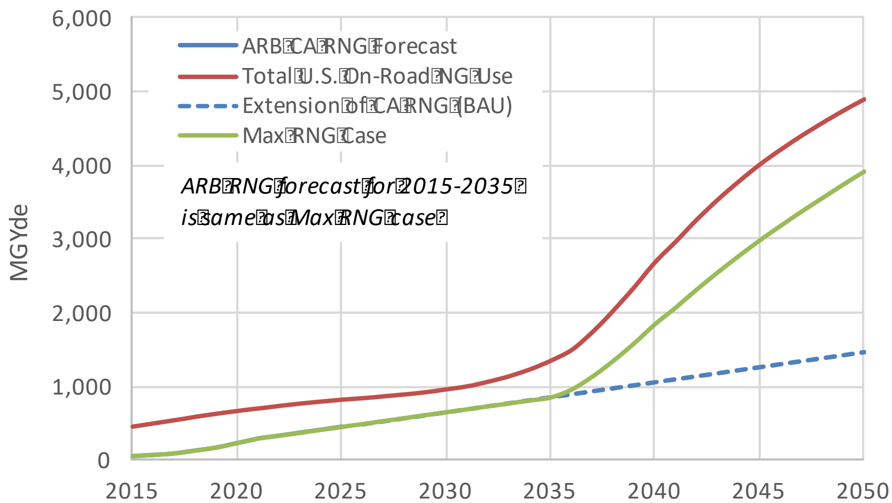


Figure 2-18. AEO2016 projected renewable and fossil natural gas volumes

2.7 Fuel Carbon Intensity

To quantify GHG emissions in this analysis, carbon intensity (CI) values for each fuel type were used. CI is defined as the mass of GHG emissions per unit energy of fuel; the quantity of fuel used is multiplied by its CI to determine GHG emissions for that fuel. The GHG pollutants included are CO_2, CH_4, and N_2O[44]. Two sets of CI values were developed – one for California and one for the entire U.S. Because the analysis extends to 2050, changes in CI over time are quantified. Key considerations for the time-dependent estimates are crude oil origin and type, natural gas sources and leakage rates, and electricity generation resource mix.

[44] GHGs = CO_2 + GWP_{CH4}*CH_4 + GWP_{N2O}*N_2O where the GWP values are Global Warming Potential factors. The AR5 values were used in this analysis: 1 for CO_2, 30 for CH_4, and 265 for N_2O. For the California analysis, the values used by ARB for the LCFS were used: 1 for CO_2, 25 for CH_4, and 298 for N_2O.

The CI values reflect not just vehicle emissions but also the emissions from producing and transporting the fuel; the lifecycle or well-to-wheel emissions. For each step in a fuel's life cycle, the direct and upstream GHG emissions are estimated. Direct emissions are calculated based on an assumed process efficiency that dictates the total amount of fuel consumed per unit of product produced. The total fuel consumption is split among different fuel types (e.g. crude oil, residual oil, gasoline, natural gas, electricity, etc.). For each fuel type, the portion consumed in each different type of combustion equipment is also assumed. Non-combustion emissions such as venting are also included. These assumptions (process efficiency, fuel shares, combustion device shares, other process emissions) form the basis to calculate the total direct GHG emissions.

Upstream emissions are generated in production and transport of process fuels directly consumed. For example, a process might specify that an amount of natural gas is combusted in a boiler. The direct emissions of natural gas combustion in a boiler are quantified, and the upstream emissions associated with natural gas recovery, processing, transmission and distribution are added. Inclusion of the upstream emissions renders the calculations iterative, and changes to one fuel pathway affect all pathways that utilize that fuel. For example, changes in assumptions about natural gas recovery affect not only the CI of compressed natural gas (CNG), but also the CI values for all fuels that utilize natural gas as a process fuel in their production. The sections below provide CI values used in the U.S. and California analyses.

U.S. Average Carbon Intensity Values

Carbon intensity values utilized in the U.S. analysis were calculated for 2015, 2020, and 2040 using Argonne National Laboratory's GREET model.[45] CI is assumed to change linearly for the periods 2015 to 2020 and 2020 to 2040; 2050 values are assumed to be equal to 2040. The GREET1_2015 model was modified to develop CI values for this analysis with updated assumptions of natural gas recovery leakage rates, crude slates, and refining efficiency.[46] Please refer to Appendix B for a detailed discussion of the GREET modeling effort.

One key input for the CI calculation of most fuels is the resource mix that is utilized to generate electricity. The base case for this analysis utilizes the AEO2016 reference case which assumes implementation of EPA's Clean Power Plan (CPP). The CPP was finalized but stayed by the U.S. Supreme Court in February of 2016 to allow the U.S. Court of Appeals for the District of Columbia to review whether EPA overstepped its bounds. The stay was extended in August of 2017 which was followed by EPA's October 2017 announcement of its intention to repeal the Clean Power Plan.[47] Given this an additional set of CI values was also generated using AEO2016's side case without the CPP. Finally, an optimistic set of CI values was calculated assuming coal generation ceases by 2040 (70% non-fossil case).

[45] Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model.
[46] Updates are based on Argonne's recent release of GREET1_2016
[47] Docket EPA-HQ-OAR-2017-0355

Table 2-2 summarizes the average generation mix for the two AEO2016 cases while the grid mix profile for the 70% non-fossil case is shown in Table 2-3. Note that the grid mix affects CI values for all the fuels because their production requires electricity.

Figure 2-19 provides the 2040 CI values for neat fuels; Figure 2-20 shows the 2040 values for finished fuels with EERs applied to correct for differences in vehicle fuel economy. Electrification with a very clean grid (70% Non-Fossil) is significantly lower than all the other options. Eliminating the CPP increases BEV emissions by 22% in 2040.

Table 2-2. Projections of U.S. average electricity generation resource mix

	AEO2016 Reference					AEO2016 Reference w/o CPP				
	Oil	NG	Coal	Nuclear	Renew-able	Oil	NG	Coal	Nuclear	Renew-able
2015	1%	26%	37%	22%	14%	1%	26%	37%	22%	14%
2020	0%	22%	37%	21%	20%	0%	22%	38%	21%	19%
2025	0%	24%	31%	21%	23%	0%	23%	37%	20%	20%
2030	0%	29%	25%	21%	25%	0%	24%	35%	20%	20%
2035	0%	28%	24%	20%	27%	0%	25%	34%	19%	22%
2040	0%	29%	22%	20%	28%	0%	26%	32%	19%	23%

Table 2-3. Grid mix for 70% non-fossil CI case

	AEO Projection				
	Oil	NG	Coal	Nuclear	Renew-able
2015	1%	26%	37%	22%	14%
2020	0%	22%	30%	21%	27%
2025	0%	24%	23%	21%	32%
2030	0%	29%	15%	21%	35%
2035	0%	28%	8%	20%	43%
2040	0%	30%	0%	20%	50%

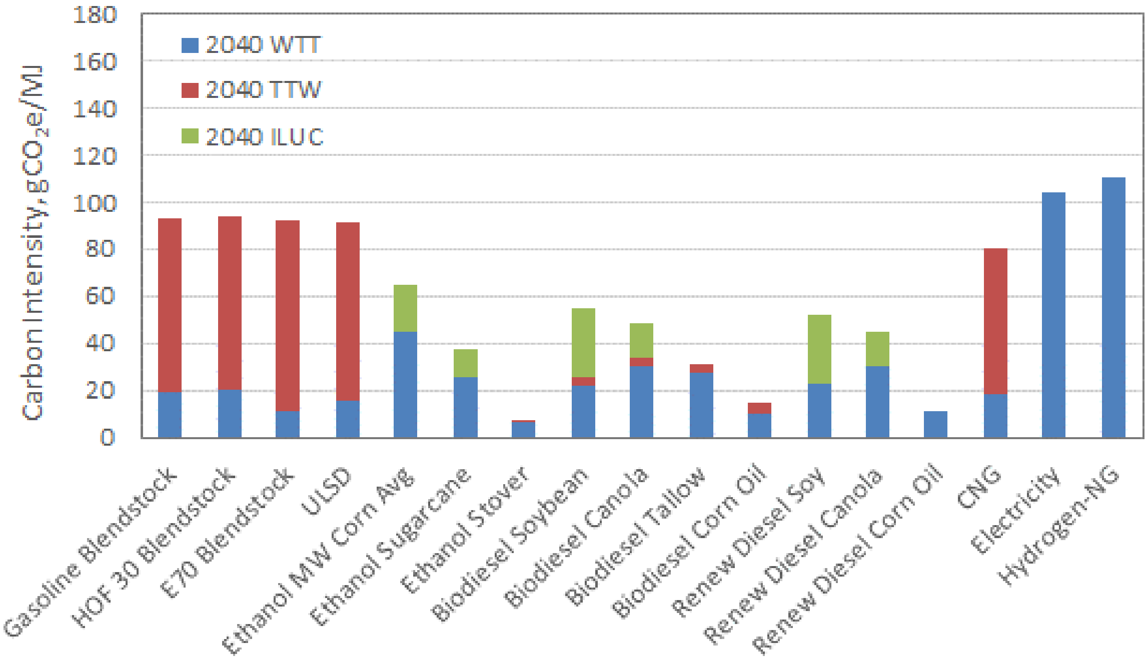


Figure 2-19. Estimated 2040 CI values (Base case; ILUC is Indirect Land Use Change, MW is Mid-West, ULSD is Ultra-Low Sulfur Diesel)

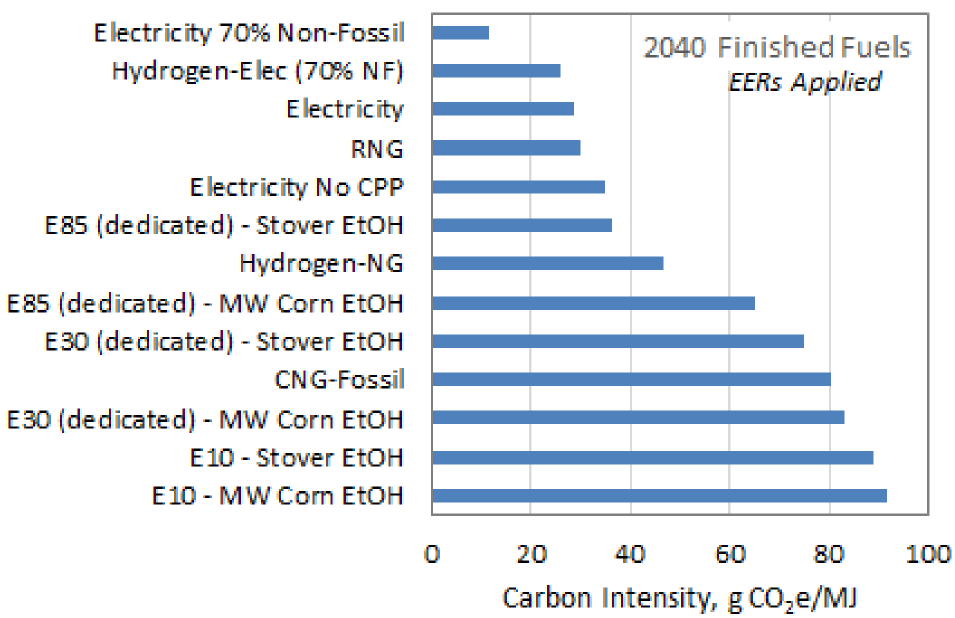


Figure 2-20. Carbon intensity values for U.S. finished fuels (BEV and FCV EER applied)

California Carbon Intensity Values

For the California analysis, CI values for all fuels except electricity and hydrogen were taken directly from ARB's most recent LCFS compliance scenario.[48] The ARB scenario extends to 2025. ARB did not breakout CI values for ethanol or biodiesel produced from various feedstocks. Instead they developed composite ethanol and biodiesel values based on their projected LCFS compliance and these values where used in the analysis. For the base case, it is assumed that the composite ethanol and composite biodiesel CI values are constant from 2025 to 2050. For electricity, the analysis used ARB's CA-GREET2 model to capture the 2025 Diablo Canyon retirement and the 2030 50% renewables requirement. A low-CI case for 2050 included 70% non-fossil generation. CI values for gasoline blend stock (CARBOB), and ultra-low sulfur diesel (ULSD), and CNG for 2025-2050 were recalculated with the changing electricity grid mix.

California law requires that 33% of hydrogen sold be generated from renewable resources. Two different hydrogen compliance pathways were run through CA-GREET (with the updated electricity grid mixes): Electrolysis with 100% renewable electricity and on-site natural gas steam reforming. The composite hydrogen value includes 33% of the electrolysis pathway and 67% of the natural gas pathway.

The CI values for neat and composite fuels in the California analysis are provided in Figure 2-21. The values for finished fuels with EER applied are shown in Figure 2-22. The hydrogen FCV using hydrogen produced from 100% renewable electrolysis has the lowest emissions, while the natural gas reforming hydrogen pathway emissions produce 50% fewer GHG emissions than gasoline. The California electricity pathway produces extremely low emissions, while high-percentage cellulosic ethanol blends offer significant reductions using liquid fuels. Appendix C includes more detail regarding the California CI calculations.

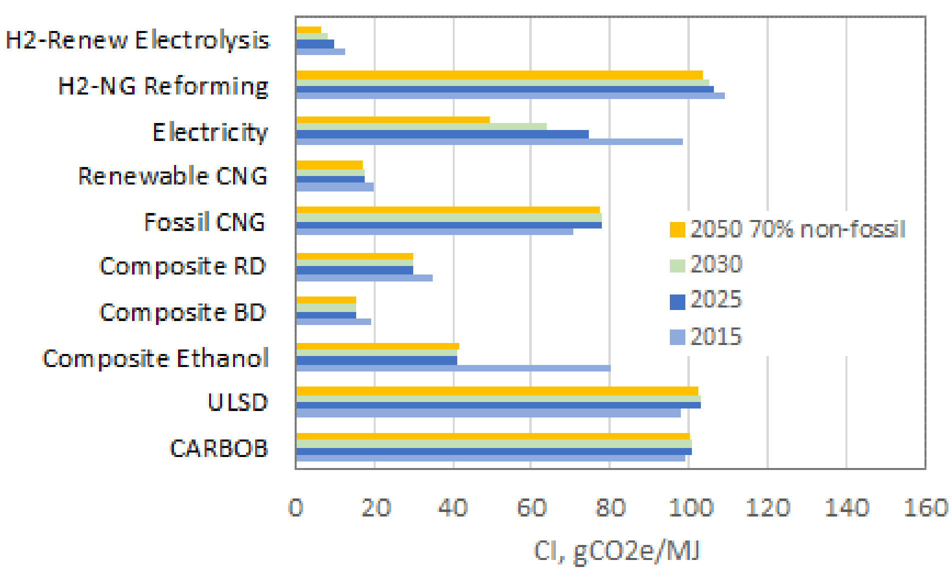


Figure 2-21. California carbon intensity values for fuels

[48] ARB LCFS Illustrative Compliance Scenario, 4-1-15.

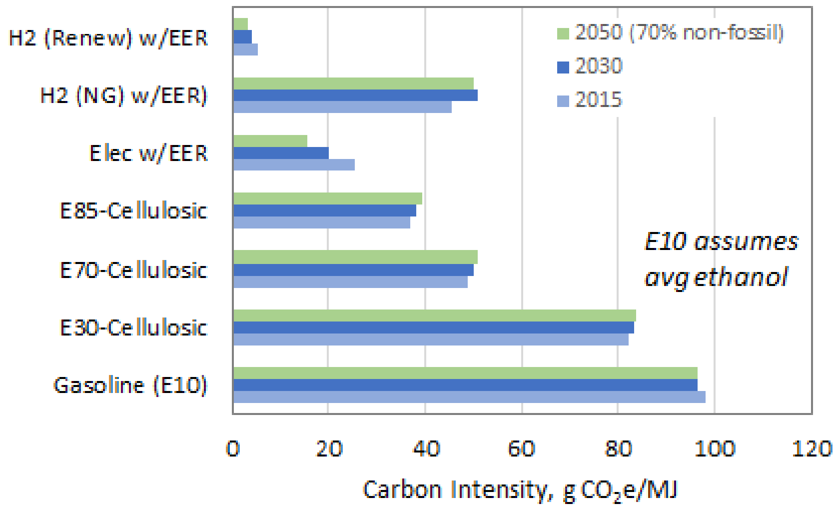


Figure 2-22. California CI values for finished fuels (BEV/FCV EER applied)

There are differences between the California and U.S. average CI values, due to several reasons including source of feedstock and feedstock transport distances, electricity grid mix for fuel production, and transportation of final fuel. California gasoline and diesel CI values are about 8% higher than the U.S. average due to crude sources and more energy intensive refining requirements. The most striking difference between California and U.S. average CI values is for electricity. In 2025, the California CI is projected to be slightly more than half of the U.S. value (74 vs 136-138 g/MJ). By 2050, California will be down to 64 g/MJ as compared to 104 (with Clean Power Plan) or 127 (without Clean Power Plan) in the U.S. overall.

2.8 Incremental Vehicle Price Estimates

Because fuel economy and incremental cost are connected, the same studies[49] utilized to define fuel economy forecasts in Section 2.5 were used to project incremental vehicle prices for the different technologies over time. Each study consulted provides incremental vehicle cost on a retail price equivalent basis. In this analysis, the phrase incremental vehicle cost means the incremental price paid by consumers relative to a 2015 ICE vehicle. For vehicle technologies with a comparable gasoline ICE version, it was also possible to determine a current incremental price based on the differences in 2016 manufacturer suggested retail price (MSRP). Some technologies had significant incremental price disagreement between the studies. Appendix A provides detailed incremental price forecasts for each technology by the studies consulted and the rationale for establishing the incremental technology costs for this analysis.

The same incremental costs were used for the U.S. and California analyses because the fuel economy values are the same except for slight differences for gasoline ICE and diesel vehicles. Figure 2-23 and Figure 2-24 provide the LDA and LDT incremental vehicle price, respectively. Table 2-4 provides this information in tabular form. Note that the consolidated BEV category in the California analysis used a market share weighted average of the BEV100 and BEV200 incremental prices.

[49] NAS Transitions, EPA MTE, EPA Draft MTE, NHTSA Draft MTE, Argonne C2G, AEO2016

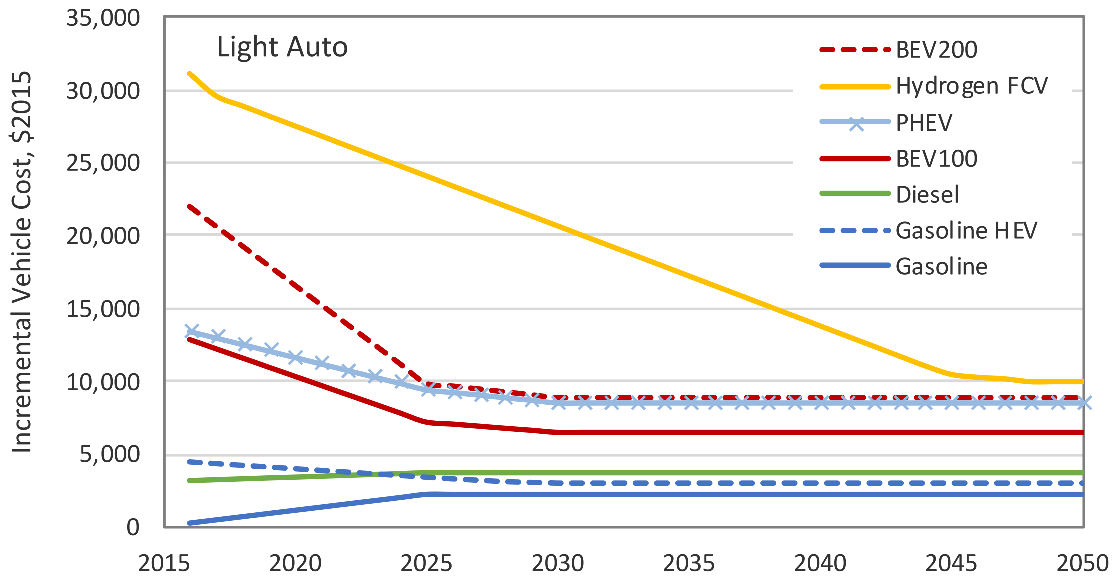


Figure 2-23. LDA incremental vehicle price

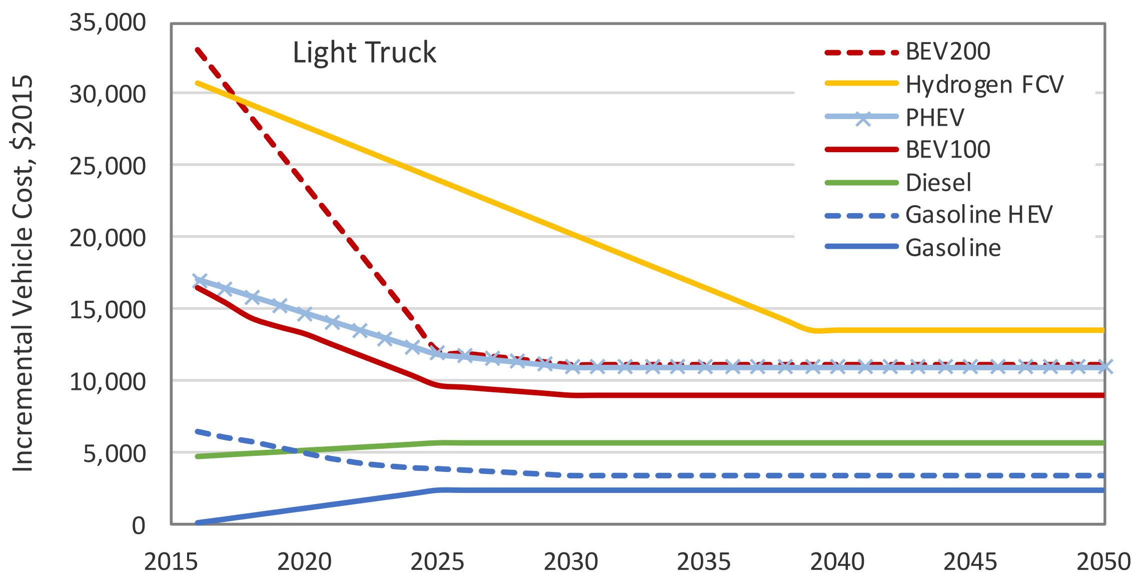


Figure 2-24. LDT incremental price

Table 2-4. Summary of incremental vehicle prices relative to 2015 ICE, $2015

	LDA			LDT		
	2015	2025	2050	2015	2025	2050
Gasoline ICE	0	2,149	2,149	0	2,438	2,438
Diesel	3,100	3,800	3,800	4,600	5,770	5,770
CNG	x	x	x	9,500	11,938	11,938
Gasoline HEV	4,484	3,416	3,000	6,500	3,884	3,400
PHEV	13,500	9,500	8,600	17,000	11,900	11,000
BEV-100	12,800	7,200	6,500	16,500	9,700	9,000
BEV-200	22,000	9,800	8,800	33,000	12,181	11,200
Hydrogen FCV	31,190	24,159	10,000	30,744	24,050	13,638
E30 ICE (RON 100)	226	2,375	2,375	320	2,759	2,759
E30 HEV (RON 100)	4,710	3,526	3,226	6,820	4,020	3,920
E70 ICE (RON 103)	320	2,470	2,470	415	2,853	2,853
E70 HEV (RON 103)	4,804	3,620	3,320	6,915	4,115	4,015

An interesting finding is that electric vehicle costs are assumed to reach economy of scale and be fully learned by 2025, which means that five manufacturers will have each produced 500,000 electric vehicles. The ZEV Mandate requires 3.3 million ZEV sales by 2025[50] in California and 9 additional states. This corresponds to approximately 6 manufacturers reaching 500,000 vehicles by 2025. Figure 2-25 shows the cumulative ZEV sales predicted by the VISION model used in this analysis for the BAU case (based on new vehicle sales and technology share assumptions presented in the previous sections). This contrasts with FCVs which are not anticipated to reach fully learned costs until 2040.

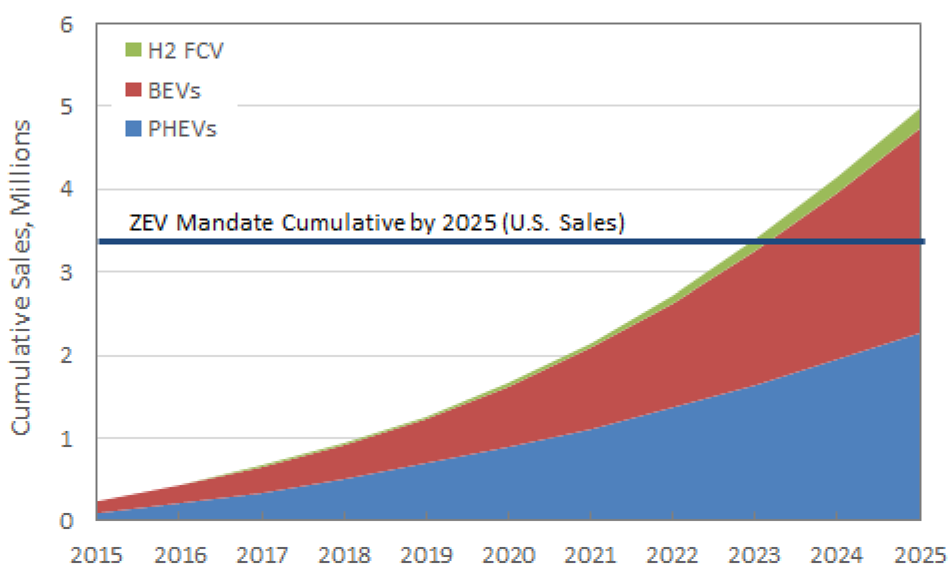


Figure 2-25. Comparison of BAU ZEV sales to ZEV mandate

[50] Alliance of Automobile Manufacturers ZEV Facts website

2.9 Fuel Price Projections

Fuel price projections for gasoline, diesel, CNG, E85 and electricity were taken directly from AEO2016 reference case for the U.S. analysis and from AEO2016 Pacific Region reference case for the California analysis. Figure 2-26 shows the U.S. projections while Figure 2-27 illustrates California fuel prices. Pacific region prices for each fuel are higher than the U.S. average.

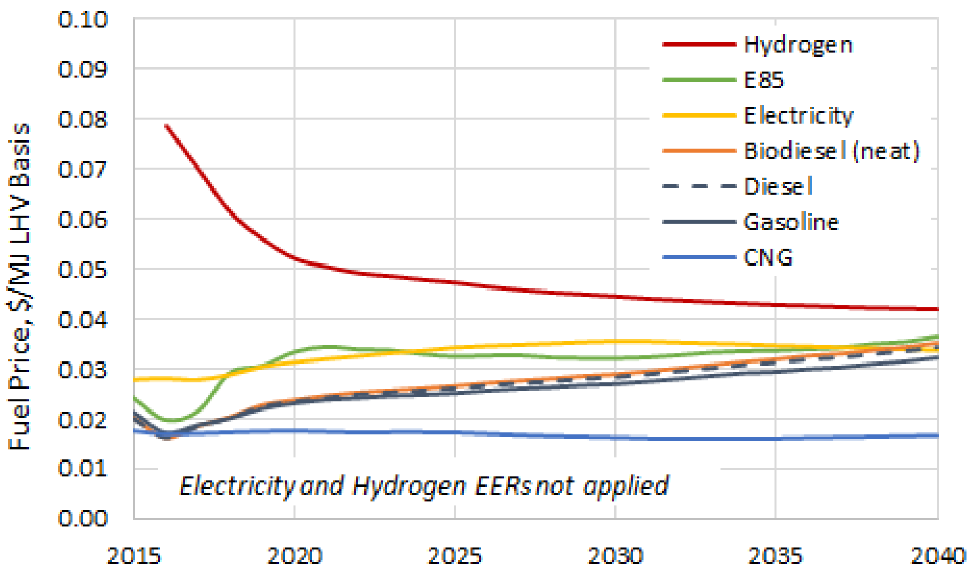


Figure 2-26. Fuel price forecast for the U.S. analysis (with Clean Power Plan)

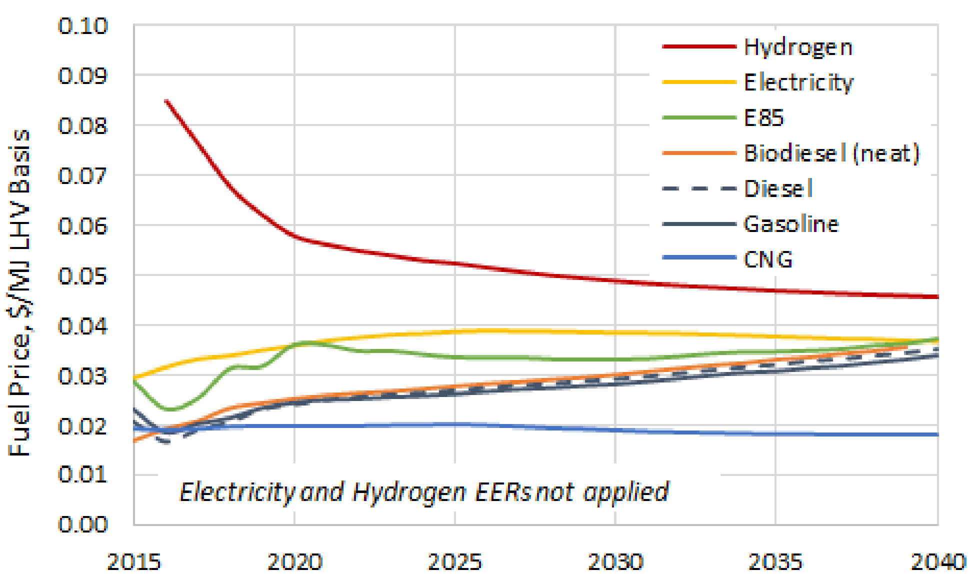


Figure 2-27. Fuel price forecast for the California analysis

The AEO2016 fuel prices in this analysis are from the reference case, which includes implementation of the Clean Power Plan (CPP). AEO2016 has a side case without the CPP. AEO2016 side case fuel prices without CPP were compared to the AEO2016 reference case prices with CPP and we found that only electricity prices are different. Figure 2-28 illustrates the difference in projected U.S. transportation electricity prices for the reference case and the side case without the CPP. In 2030, the reference case electricity prices are ~ 5% higher than the side case. For this analysis, the reference case prices are used.

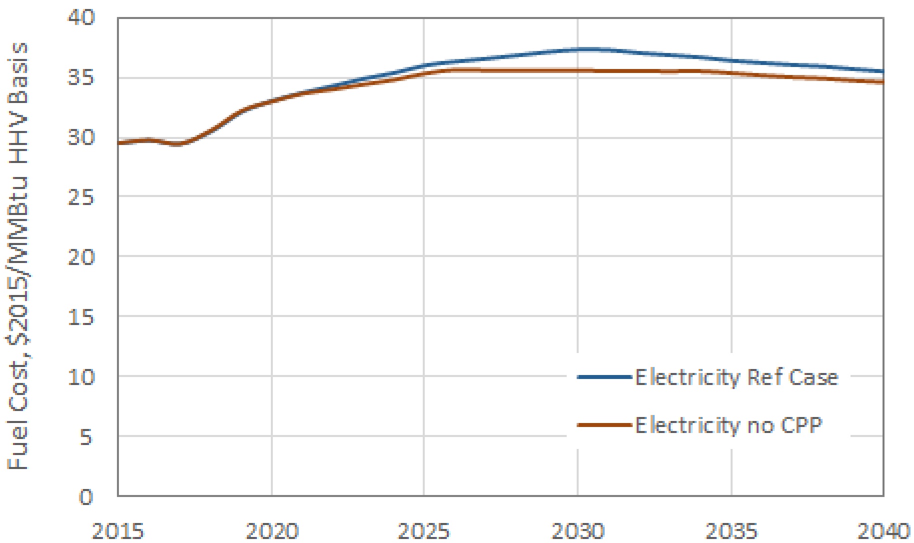


Figure 2-28. AEO2016 reference case and no CPP case transportation electricity prices

AEO2016 does not provide a price for biodiesel. However, based on conversations with producers and representatives of the National Biodiesel Board, biodiesel sells at a discount to diesel on a per gallon basis. In 2014 (100$ crude) the wholesale discount was 25 cent/gal or about 6.5% (3.82 $/gal in 2014). Consequently, this analysis assumes a 6.5% discount. At today's price ($2.70), this amounts to 18 cents per gallon. For renewable diesel (not shown), Propel offers a 3% to 5% discount relative to diesel. This analysis uses an average 4% discount for renewable diesel.

Hydrogen prices are also omitted from AEO2016 forecasts. Hydrogen fuel prices in this analysis are based on current hydrogen fuel prices at California refueling stations (13 $/kg)[51], AEO2016 projections of industrial natural gas and electricity prices, and volume scaling factors. Two different price projections were developed for the U.S. and California analyses: a price for on-site natural gas steam reforming (NGSR) and a price for electrolysis. The U.S. analysis assumes that all the hydrogen is produced from natural gas. For California, it is assumed that one third is produced from electrolysis and the balance from natural gas steam reforming. This satisfies the California requirement that one third of hydrogen produced must be renewable.

[51] http://www.altfuelprices.com/stations/HY/CA

Figure 2-29 shows the hydrogen production and delivery cost scaling factors. The U.S. hydrogen demand curve is based on projections with assumed FCV market shares and vehicle fuel economy. The chart also provides the volume-dependent factors for fuel production and delivery. These scaling factors project fuel production costs and provide the basis for cost reductions due to economy of scale and learning.

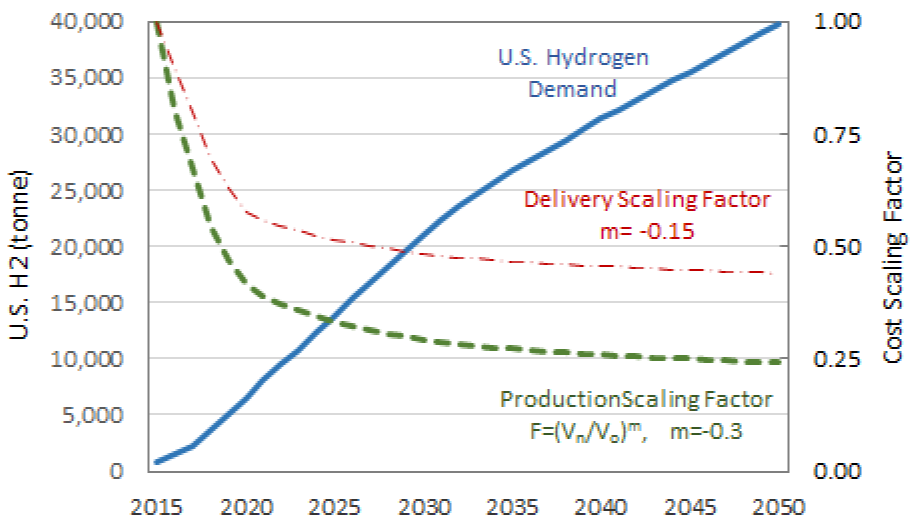


Figure 2-29. Hydrogen production scaling factors

The scaling factors were applied to the hydrogen cost buildups for electrolysis and NGSR pathways to generate fuel prices as a function of time (volume) for the U.S. and California. Figure 2-30 compares the prices developed by LCA to the future prices estimated by the Department of Energy's H2A program[52]. The California and U.S. industrial natural gas prices are nearly identical, resulting in identical prices for hydrogen produced from natural gas. In contrast, industrial electricity prices are forecast to be significantly lower in California than in the U.S. (possibly due to higher renewable content), resulting in a lower electrolysis hydrogen price in California than in the U.S. in general. This contrasts with the transportation electricity prices. California transportation electricity prices are markedly higher than the U.S. average price.

[52] https://www.hydrogen.energy.gov/h2a_analysis.html

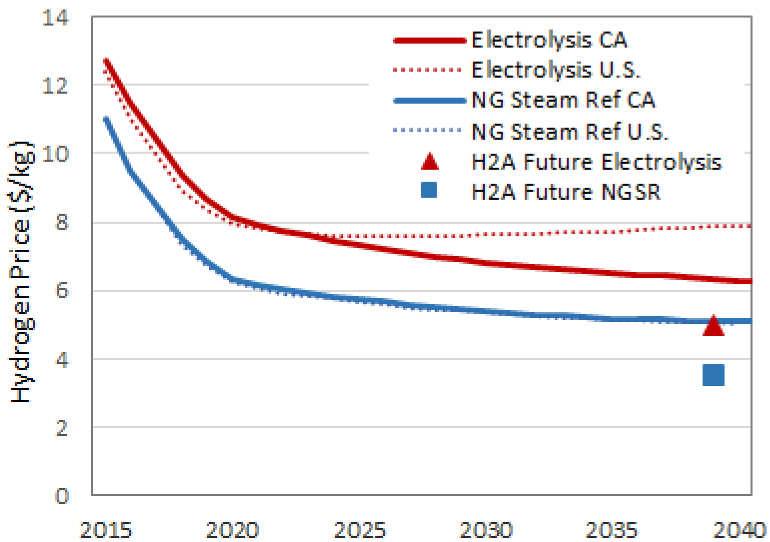


Figure 2-30. LCA estimated hydrogen fuel prices

The Renewable Fuels Standard (RFS) adds to biofuel costs. The RFS requires volumes of different types of renewable fuel to be sold each year and volumes are tracked with renewable identification numbers (RINS) generated by renewable fuel producers. RINS can be detached from actual gallons and sold to regulated parties to meet compliance obligations. Table 2-5 shows assumed costs for the various RIN types. In addition to RINs, cellulosic ethanol producers receive a $1.01 per gallon tax credit. Biodiesel and renewable diesel producers also receive a $1 per gallon credit. These credits were extended by Congress through 2017. This analysis assumes that the credits continue to be renewed through 2025 and are discontinued thereafter.

Table 2-5. RIN definitions and assumed values

RIN Label	Fuel Types	Current Value ($/RIN)	RINS per gal
D3	Cellulosic Ethanol, Renewable NG	1.76	1
D4	Biodiesel, Renewable Diesel	0.82	1.5
D5	Advanced Ethanol (e.g. sugarcane)	0.89	1
D6	Renewable Fuel (e.g. corn ethanol)	0.76	1

Production costs of cellulosic ethanol are estimated to be $0.80 to $1.30 per gallon more expensive than conventional ethanol. Cellulosic ethanol in this analysis is assigned the market price of ethanol (whether consumed as RFG or E85) and an extra dollar cost or higher as estimated by the difference between the D3 RIN premium over D6 RIN price. This results in a $2 premium per gallon for cellulosic ethanol for 2016-2025 and $1 per gallon for 2026-2050. For high volume cellulosic ethanol use scenarios, it might be expected that the cellulosic premium decreases to less than $1 per gallon due to learning and economies of scale. This uncertainty in cellulosic ethanol cost is addressed in Section 5.7—Sensitivity Tests.

The situation for CNG produced from renewable natural gas (RNG) is similar. RNG is recovered from landfills and produced by digesters at dairies and waste water treatment (WWT) plants. Digesters can also produce RNG from municipal solid waste (MSW). In all cases, the raw gas is cleaned to pipeline quality and injected into the natural gas pipeline system. A recent UC Davis analysis[53] developed RNG cost estimates for each feedstock that includes collection, cleanup and pipeline injection. Costs are presented as a function of volume, with cost increasing as volume increases, reflecting less economically feasible projects coming on-line as demand increases. Table 2-6 summarizes the RNG costs for each feedstock at half of the California potential volume and at approximately 90% of California potential volume.

Assuming 90% of the RNG currently used is recovered landfill gas, 9.5% is from WWT digesters and that the balance is split between MSW and dairy digesters and assuming half-potential volume costs (the half-potential volume costs are similar to minimum volume costs), the resulting 2016 cost to get RNG into the natural gas distribution system is $8.25 per MMBtu.

Table 2-6. Cost of RNG for different feedstocks

Feedstock	Half of Potential CA Volume		~90% Potential CA Volume	
	$/MMBtu	Volume (bcf/yr)	$/MMBtu	Volume (bcf/yr)
Landfill Gas	7.5	25	15	45
MSW Digester	17.0	7.5	20	12.5
Dairy Digester	55	7	90	12.5
WWT Digester	14	3	35	6

Source: UC Davis ITS

The cost of compression and refueling is assumed to be the difference between the AEO2016 industrial natural gas price and the transportation price. This difference is $14 per MMBtu for 2016 decreasing to just over $11 per MMBtu by 2050. The Pacific and U.S. average increments are nearly identical. This increment brings the 2016 RNG-CNG price $23.5 per MMBtu (LHV basis). The fossil CNG price for 2016 is just under $18 per MMBtu (LHV), making RNG-CNG $5.5 per MMBtu (31%) more expensive than fossil CNG.

To encourage the use of RNG-CNG, RNG is a cellulosic biofuel under the RFS program and therefore generate D3 RINs, which were assumed at $1.76 per gal ethanol ($23 per MMBtu). This RIN value more than offsets the current cost of producing RNG-CNG. As in the case of cellulosic ethanol, it is not clear which party pays for the RIN (producer, obligated party, consumer). Consistent with the treatment of cellulosic ethanol pricing, this analysis assigns CNG produced from RNG the market price of fossil CNG and a premium of $1 per RIN produced is assessed as a proxy for higher production costs.

[53] "The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute", UC Davis Institute for Transportation Studies (Myers-Jaffe, Parker, Dominguez-Faus, Scheitrum, Wilcock, Miller), Dec 2016.

2.10 Infrastructure Costs

Utilizing lower CI fuels in the transportation sector results in increased infrastructure spending to accommodate them. For example, new plants must be built to produce cellulosic ethanol and hydrogen and fueling stations must be retrofitted to store and dispense E85 and hydrogen. This analysis assumes that infrastructure costs are recovered in the price consumers pay for the fuels. One exception to this rule is the electric vehicle supply equipment (EVSE) used to charge electric vehicles. It is assumed here that 90% of BEV and 30% of PHEV purchases[54] trigger purchase and installation of a Level 2 EVSE at $1200 per unit. This is a conservative estimate that accounts for the fact that some future EV purchases will be for replacement EVs with a residential charger already in place.

[54] Center for Sustainable Energy PEV Owner Survey, Feb 2014

3. BAU Projections Compared to Climate Goals

In 2015 the U.S. signed the Paris Agreement, committing to a 26-28% reduction in GHG emissions from 2005 levels by 2025. The Obama Administration's long-term goal was an 80% reduction from 2005 levels by 2050, the same goal that was in the 2009 American Clean Energy and Security Act (Waxman-Markey) which passed in the U.S. House of Representatives but failed in the Senate. However, circumstances have markedly changed. The Trump Administration has announced its intention to exit the Paris Agreement and the EPA Administrator has professed skepticism about human contribution to climate change. Future U.S. climate goals are unclear. Nonetheless, for its assessment of progress toward climate goals, this analysis assumes that the U.S. target is 80% below 2005 levels by 2050.

Based on forecasts of vehicle sales, VMT, fuel economy, and fuel CI provided above, the well-to-wheels GHG emissions can be calculated and compared to GHG reduction goals. Figure 3-1 illustrates the resulting BAU forecast of light-duty GHG emissions. To establish 2005 GHG emissions and calculate the emission rates that correspond to the 2025 and 2050 goals, this analysis used the default fuel consumption for 2005 from the VISION model and multiplied it by the GREET default 2005 gasoline and diesel carbon intensity values. The U.S. light-duty fleet is on track to meet the 2025 Paris goal, but beginning in 2025, a 5% per year reduction is required to reduce GHG emissions by 80% by 2050.

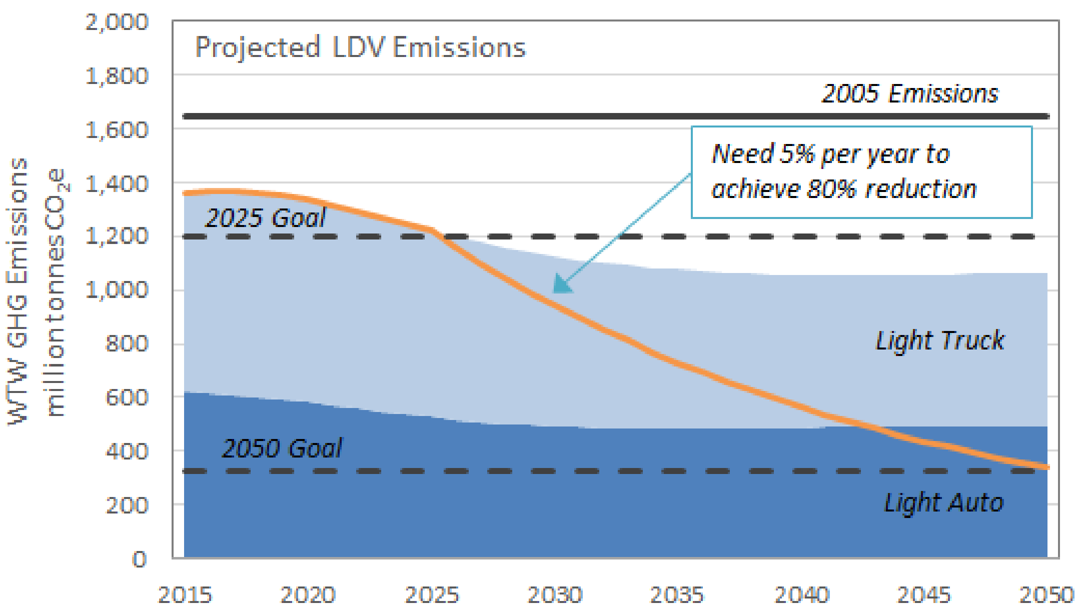


Figure 3-1. Projected U.S. light-duty GHG emissions and goals

In its Global Warming Solutions Act (AB32) and state executive orders, California established goals to reduce GHG emissions to 1990 levels by 2020[55], to reduce them to 40% below 1990 levels by 2030[56], and to 80% by 2050[57]. The California goal is more difficult than the U.S. because the baseline year is 15 years earlier when total transportation GHG emissions were lower.[58] Figure 3-2 illustrates the BAU projection of light-duty GHG emissions compared to the California goals. The estimated trajectory indicates that California will be slightly higher than 1990 levels in 2020. To attain the subsequent milestones, a 6.5% reduction per year is needed 2025-2030 and 5.5% per year for 2030-2050. These are larger than those needed to achieve the U.S. goal.

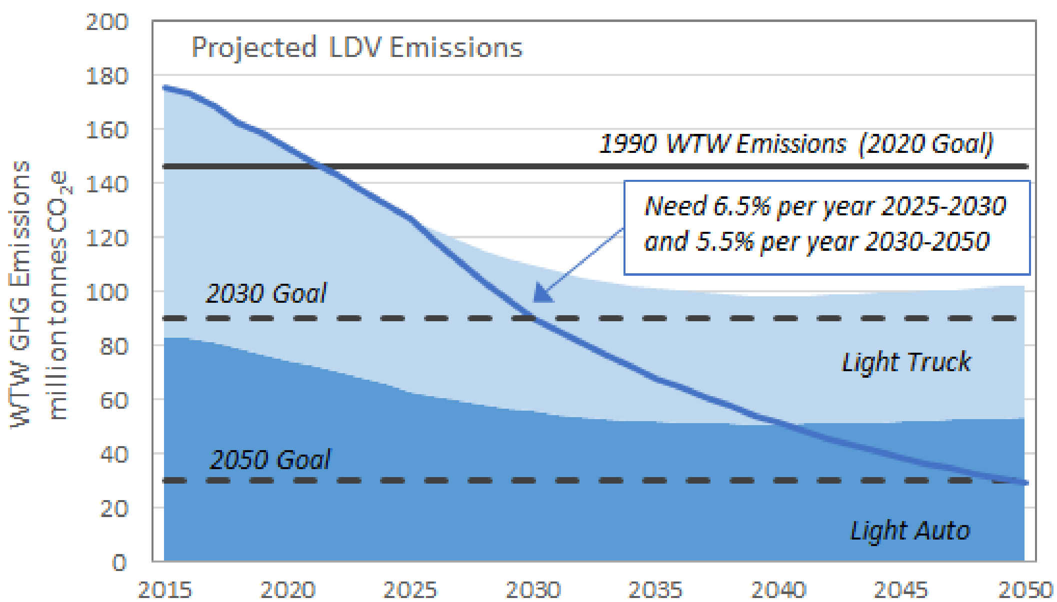


Figure 3-2. Projected California light-duty GHG emissions and goals

[55] Global Warming Solutions Act, AB32 2006

[56] Governor Brown Executive Order B-30-15, April 2015

[57] Governor Schwarzenegger Executive Order S-3-05, June 2005

[58] Per vehicle GHG emissions in 1990 were like 2005, but the total number of vehicles on the road was much lower

4. Individual Vehicle GHG Emissions

The first step in defining scenarios was to quantify the 2050 GHG emission reduction potential for each vehicle/fuel combination. Costs were then calculated to assess the relative merits of each GHG reduction scenario. The 2050 GHG emissions and incremental costs are presented below on a g/mi basis for the U.S. and California analyses.

4.1 2050 Emissions and Costs per Mile, U.S. Analysis

To achieve the 2050 GHG goal at the predicted VMT levels for the U.S., the average light-duty emission rate must achieve 86 gCO_2e/mi. Figure 4-1 illustrates the LDA emission rates for a wide range of vehicle technology and fuel combinations, assuming continued fuel economy improvements beyond 2025 (please refer to Section 2.5). The combinations that do not achieve the goal are blue. This includes all E10 and E30 ICEVs, as well as diesels and diesel HEVs regardless of fuel blend. Combinations that achieve the goal without the use of advanced ethanol or a 70% non-fossil grid are colored orange. These include the PHEV, dedicated E85 PHEV and BEV200 (even without the Clean Power Plan). Combinations that achieve the goal but require advanced ethanol, a 70% non-fossil grid or both are colored green. The lowest emission rate is for the BEV200 with 70% non-fossil grid.

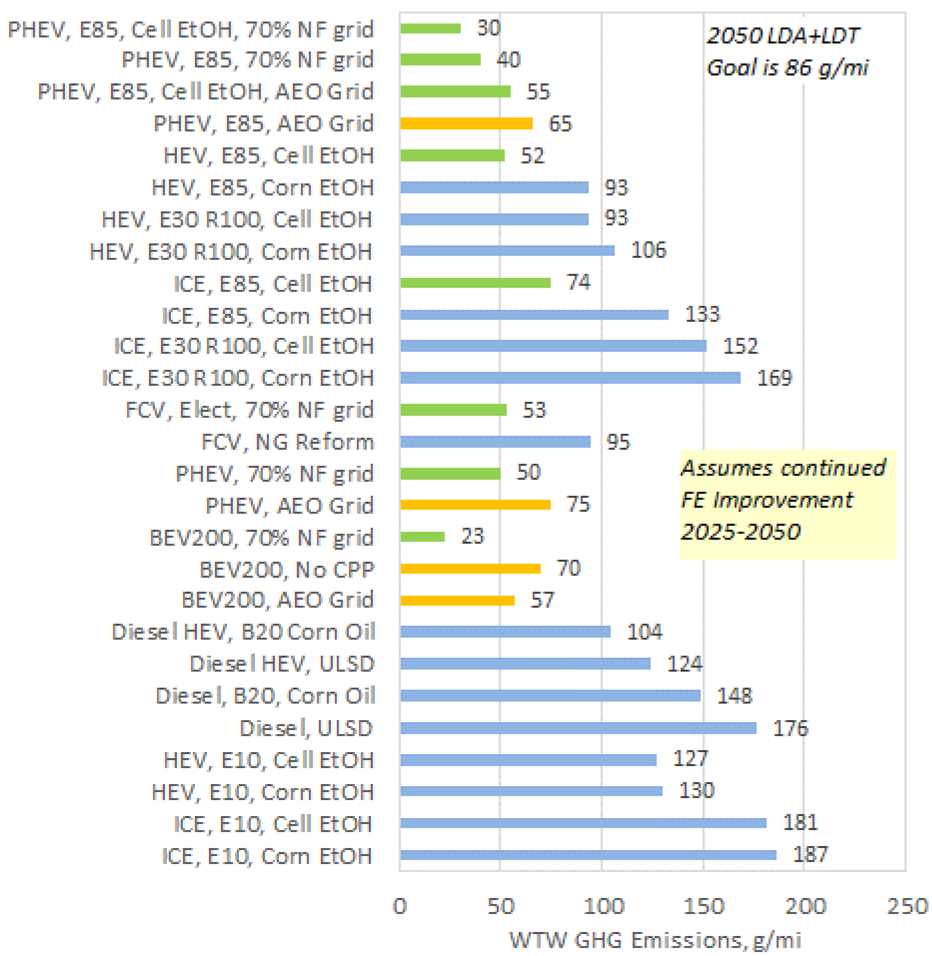


Figure 4-1. U.S. LDA emissions in 2050 with fuel economy improvement 2025-2050

Figure 4-2 shows the results without fuel economy improvements beyond 2025. In this case, only the BEV200 and the dedicated E85 PHEV combinations meet the goal without advanced ethanol and/or 70% non-fossil grid. Without the Clean Power Plan, the BEV200 does not meet the goal unless fuel economy continues to improve. Without the CPP and without continued fuel economy improvement, only E85 vehicles (dedicated ICE, HEV and PHEV) using 100% advanced ethanol meet the goal for 2050.

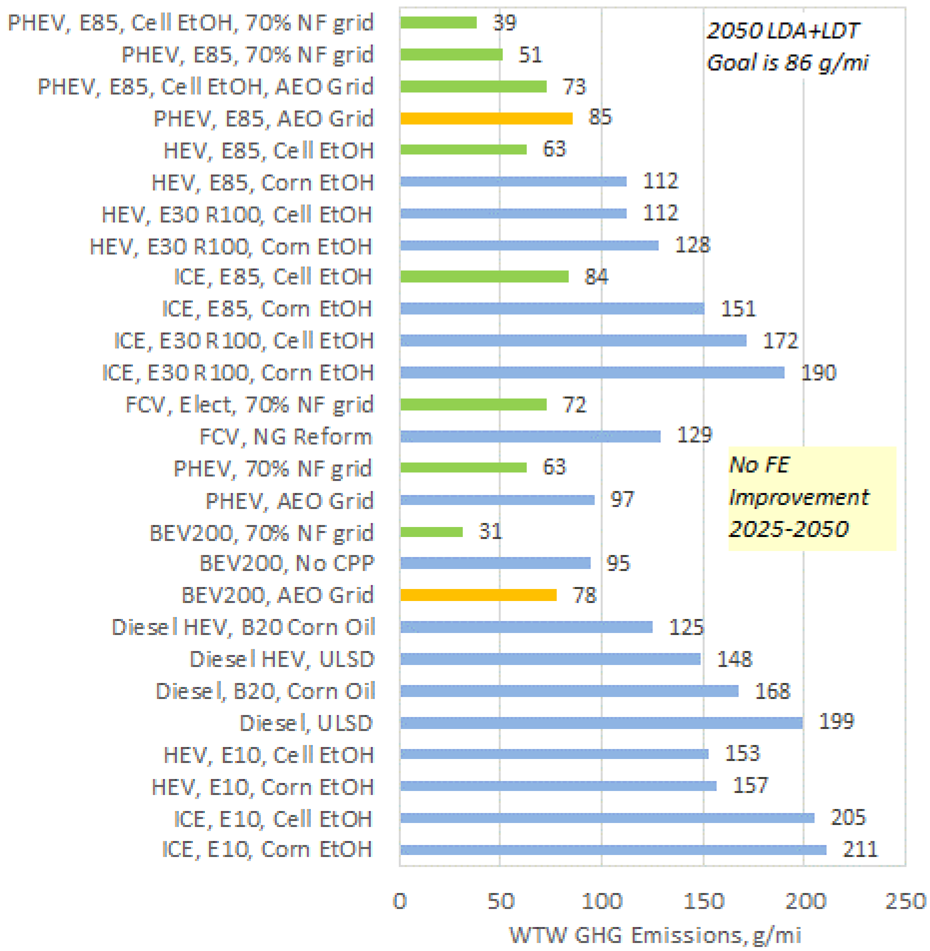


Figure 4-2. U.S. LDA emissions in 2050 with constant fuel economy for 2025-2050

Figure 4-3 shows the vehicle (incremental), fuel and charger costs per mile for each vehicle-fuel combination relative to the 2015 gasoline ICE. Vehicle costs assume 150,000 lifetime miles. Electrification options have the highest vehicle costs while options utilizing higher volumes of cellulosic ethanol have the highest fuel costs. Other costs of vehicle ownership, such as operation and maintenance are not included. These costs were examined in more detail (a net present value analysis of costs was estimated) in the Draft MTE. In this analysis, only incremental vehicle cost, fuel cost, and charging equipment cost for plug-in vehicles were considered.

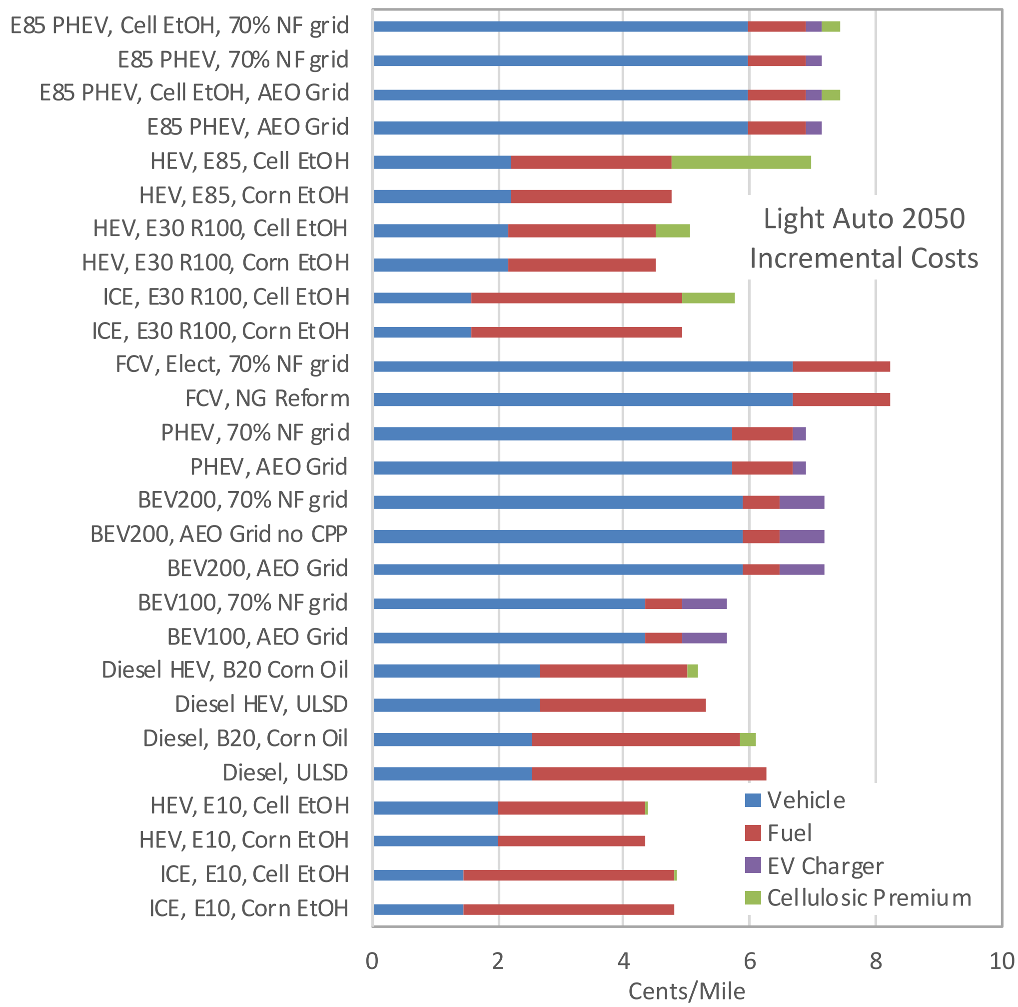


Figure 4-3. U.S. LDA costs in 2050 (with continued FE improvement 2025-2050)

Incremental cost and GHG reduction relative to 2015 gasoline ICE are combined in Figure 4-4 for the options that achieve the 2050 goal (assuming continued fuel economy improvement). The gasoline ICE vehicle costs and GHG emission reductions are also shown for reference. The vehicle/fuel combinations provide similar reductions. Apart from BEV100, all the options have similar costs with FCVs at the higher end of the range. The BEV100 options have the lowest cost at ~ 20% higher than the ICE. The values shown assume that electricity prices are the same for the low carbon grid and AEO grid mixes. The impact of electricity price on the analysis is addressed in Section 5.7.

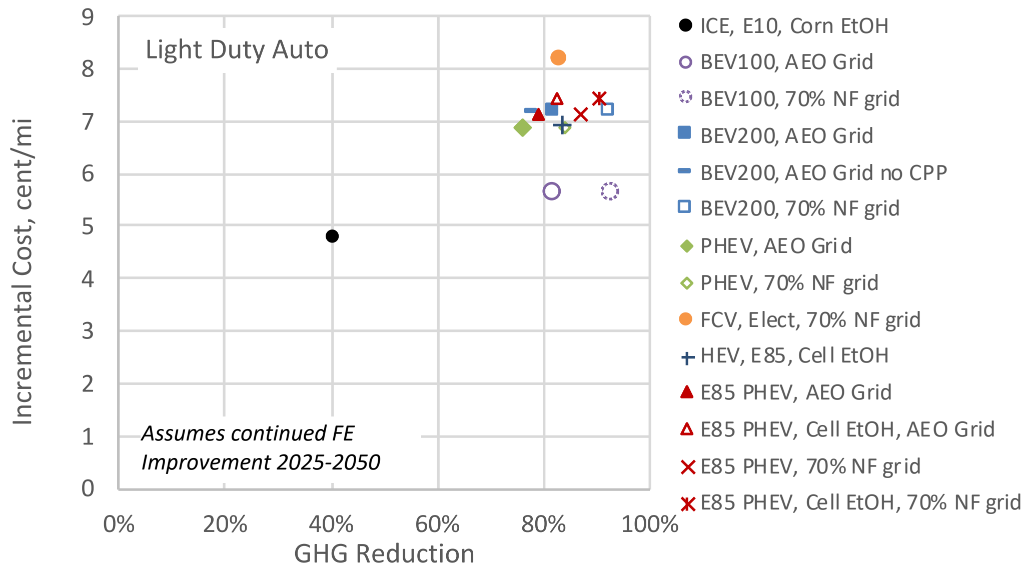


Figure 4-4. U.S. LDA incremental costs and GHG reduction in 2050

Figure 4-5 provides 2050 GHG emissions for light trucks with continuing fuel economy improvement. Vehicle/fuel combinations that do not reach the 80% reduction goal are blue. Combinations that achieve the goal without the use of advanced ethanol or a 70% non-fossil grid are colored orange. Only the BEV200 meets the goal without a low carbon grid, but not without the CPP. Combinations that achieve the goal but require advanced ethanol, a 70% non-fossil grid, or both, are colored green (E85 PHEV, E85 HEV, FCV, CNG). Without continued fuel economy (Figure 4-6), no vehicle/fuel pairings meet the goal without a low carbon grid or advanced ethanol. With a “dirty grid” and no fuel economy improvement beyond 2025, only the E85 HEV using cellulosic ethanol achieves the 2050 goal. With a "dirty grid” combined with fuel economy improvement, a CNG truck using RNG also achieves the goal. However, 86 g/mi is the LDV fleet average goal. LDTs can be slightly above the average if LDA GHG emissions are below it. For BEVs, losing the CPP reduces options for achieving the 2050 goal, illustrating the importance of decreasing electricity CI.

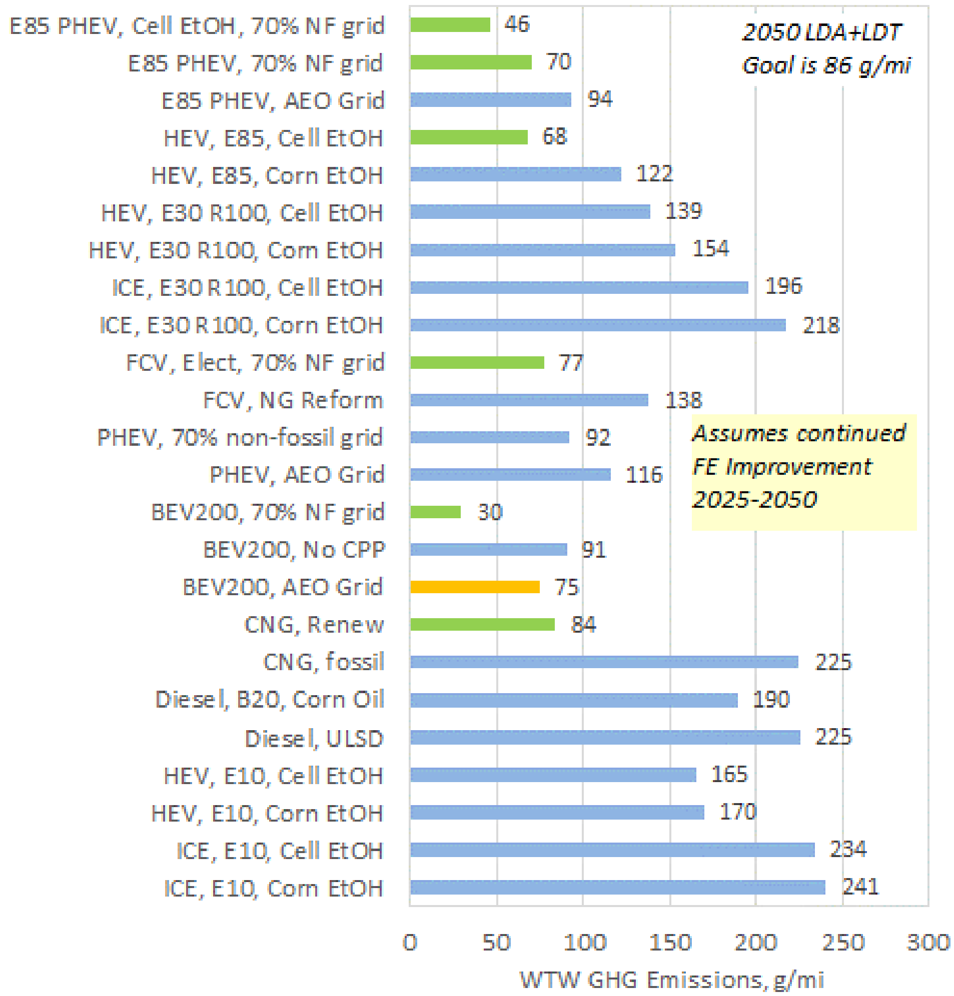


Figure 4-5. U.S. LDT emissions in 2050 with fuel economy improvement 2025-2050

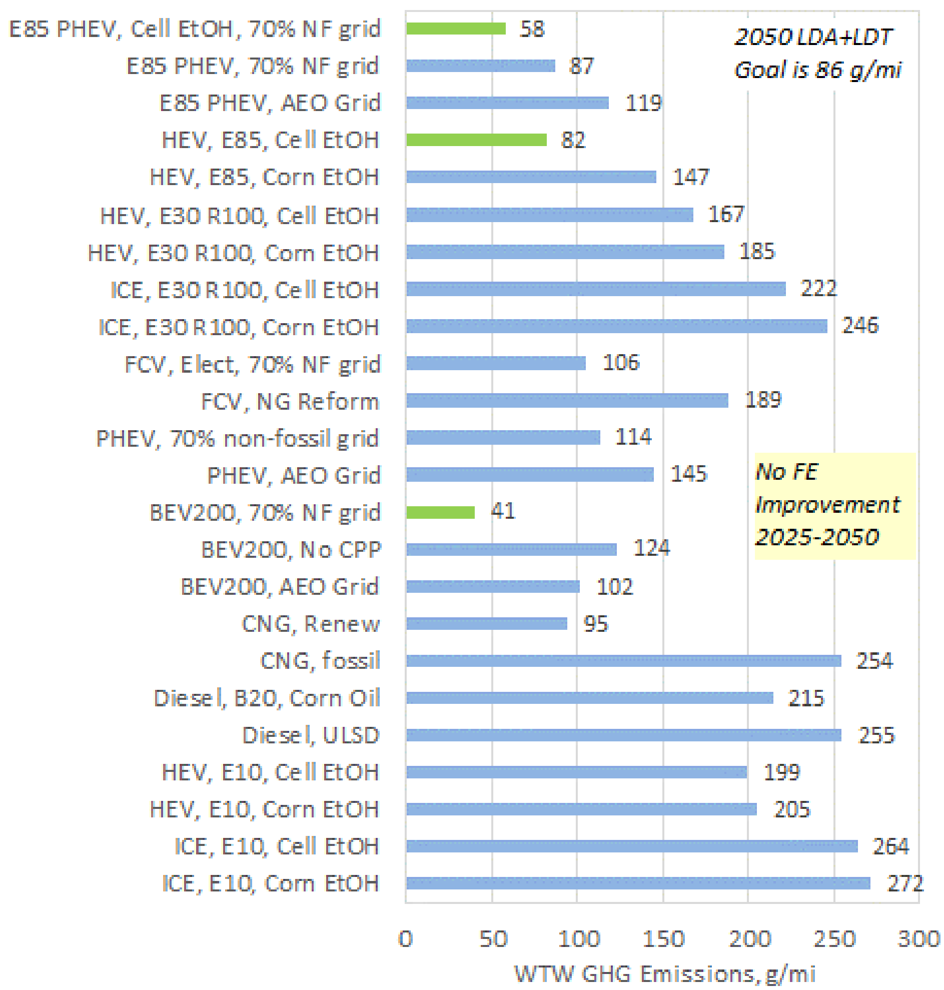


Figure 4-6. U.S. LDT emissions in 2050 with constant fuel economy for 2025-2050

Figure 4-7 provides the incremental vehicle, fuel and charger costs per mile for each LDT vehicle/fuel combination relative to the 2015 gasoline ICE. Like LDA, the per mile vehicle and EVSE costs assume 150,000 lifetime miles. Electrification and CNG options have the highest vehicle costs while E85 options have the highest fuel costs. Fuel costs for CNG are lower than gasoline, but RNG has higher costs because of the cellulosic RIN costs attached to RNG. Costs and GHG reductions with continuing fuel economy improvement are combined in Figure 4-8. The trends are similar to the LDA trends with all technologies providing similar GHG reduction. CNG and FCV options have the highest costs, the BEV200 costs are similar to PHEV and E85 HEV using cellulosic ethanol costs, and the BEV100 options have the lowest costs.

Based on the GHG reduction potential, the compliance scenarios focused on options that maximize penetration of BEVs, PHEVs, E85 PHEV, and E85 HEV and LDT CNG vehicles. Mid-level ethanol blend (E30) dedicated vehicles, diesel and hydrogen FCVs do not provide the dramatic GHG emissions reductions needed to meet the 2050 goal.

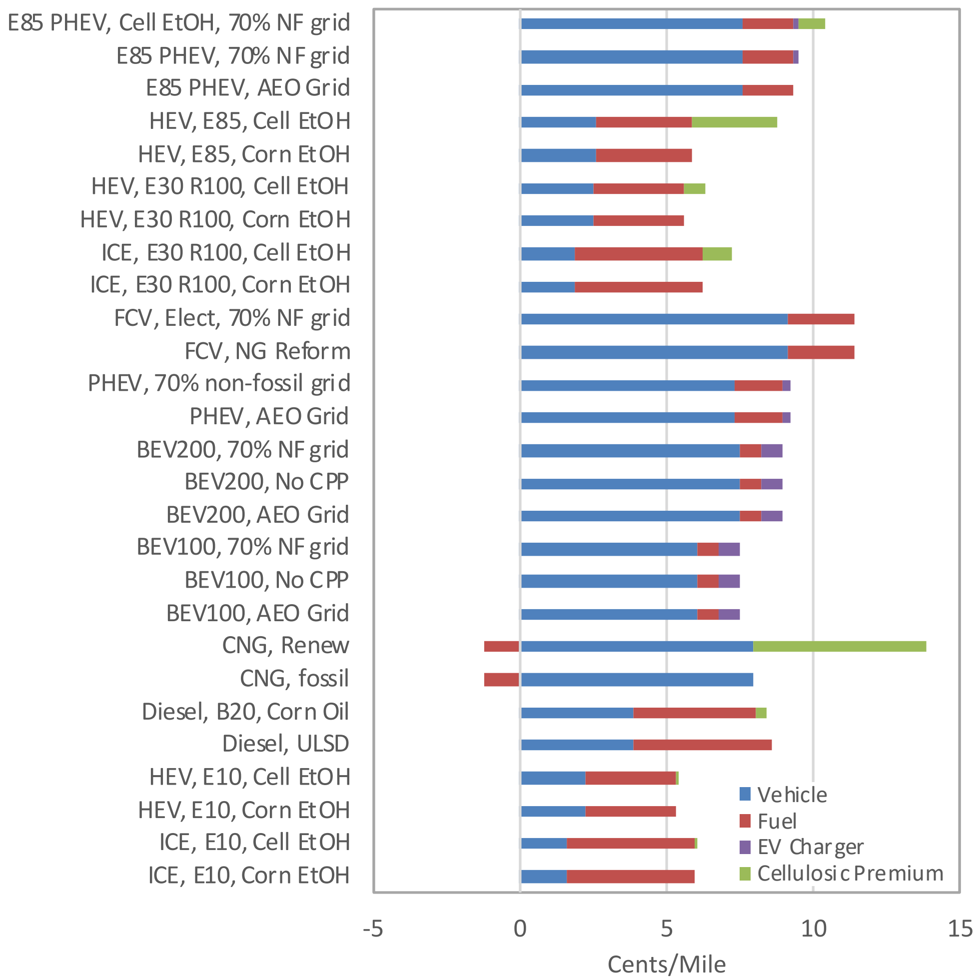


Figure 4-7. U.S. LDT costs in 2050 (with continued FE improvement 2025-2050)

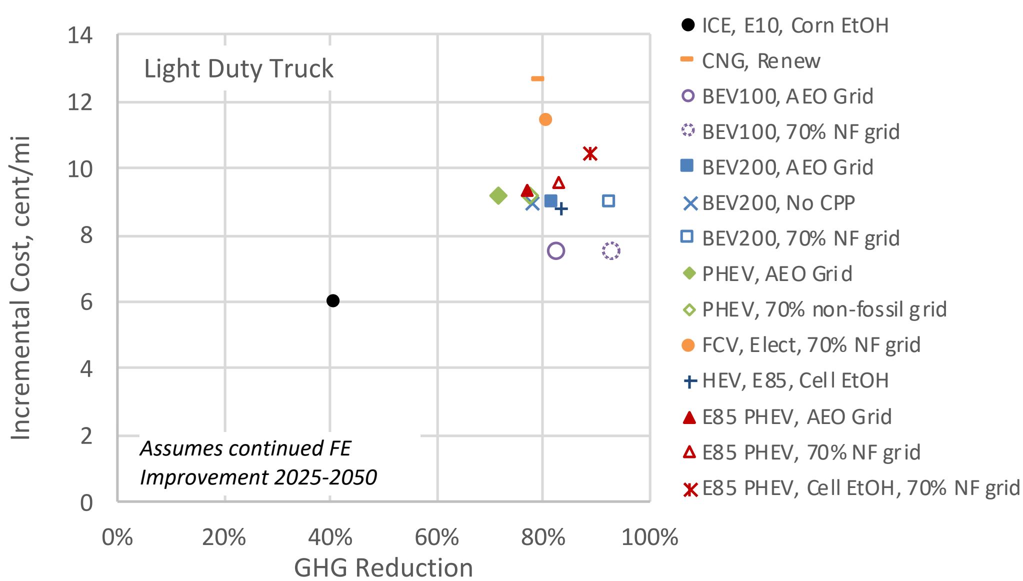


Figure 4-8. U.S. LDT 2050 costs and cumulative GHG reduction (continued FE improvement)

4.2 2050 Emissions and Costs per Mile, California Analysis

For the California analysis, LDA emission rates in 2050 are shown in Figure 4-9. The 2050 average LDV GHG emissions goal is 81 g/mi compared to the U.S. goal of 86 g/mi. Without lowering electricity and ethanol carbon content beyond BAU (carbon intensities shown in Figure 2-21), four options meet the goal (marked in orange): E85 PHEV, FCV, PHEV, and BEV[59]. Reducing grid CI reduces emission rates of the electrified options but does not enable any additional options to meet the goal. With advanced ethanol, the E85 HEV becomes a compliance strategy and the E85 PHEV emission rate drops even lower (though not quite as low as the BEV with a 70% non-fossil grid).

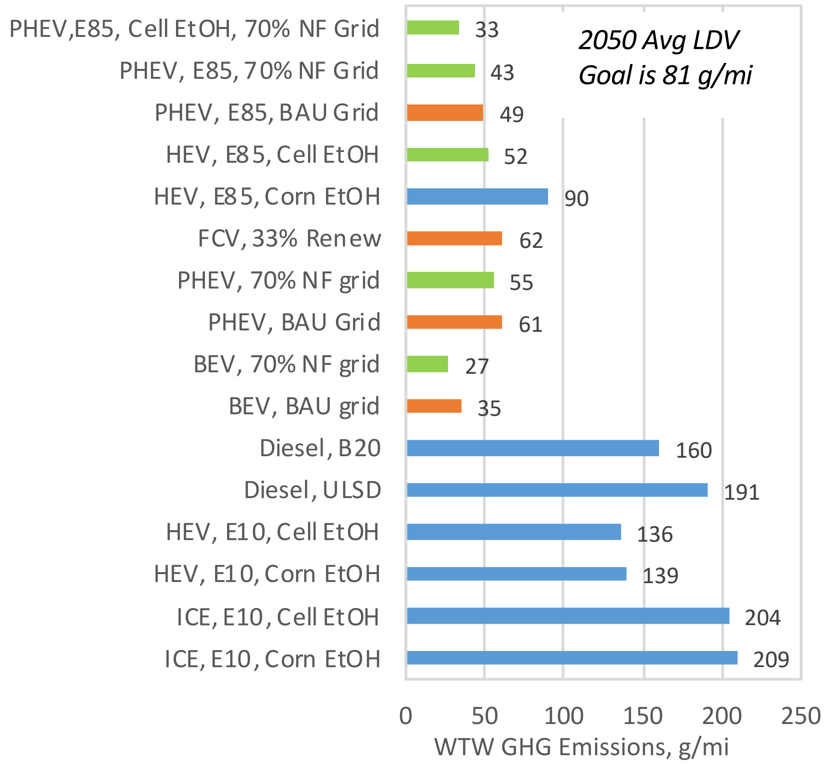


Figure 4-9. California LDA emissions in 2050 with improved fuel economy 2025-2050

Incremental cost per mile is provided in Figure 4-10 with relative contributions from vehicle, fuel, EVSE, and cellulosic fuel premium. The most expensive option is the FCV, with double the incremental cost of a 2050 ICE vehicle. The next most expensive option is the dedicated E85 PHEV. The E85 PHEV shows very little difference between cellulosic ethanol and corn ethanol because most of the LDA PHEV miles are powered by electricity. The dedicated E85 HEV is a lower cost option; if cellulosic ethanol is used, the cellulosic premium (assumed to be today's value of $1 per gallon more than corn) increases the total cost significantly. However, the supply of cellulosic ethanol required for the E85 option would likely decrease the cellulosic fuel premium. The effect of lower D3 RIN prices on the E85 HEV cellulosic case is examined in Section 5.7.

[59] ARB does not distinguish between BEV100 and BEV200. For the CA analysis, averages of the BEV100 and BEV200 U.S. fuel economy and incremental cost values are used.

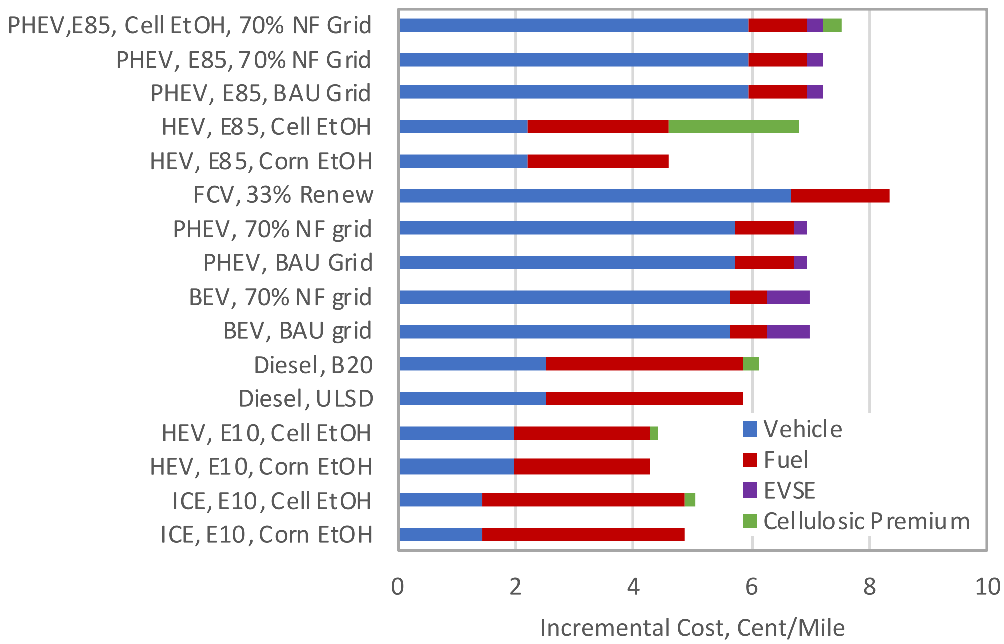


Figure 4-10. California LDA incremental costs in 2050

California LDA incremental cost is plotted as a function of GHG reduction in Figure 4-11. Most scenarios provide GHG reduction in the 80-90% range. BEVs provide the greatest GHG reductions at modest cost. In California BEVs, the reductions achieved with a 70% non-fossil grid mix are not significantly larger than those of the BAU grid mix because the BAU in California is already very low carbon. E85 HEVs using advanced ethanol have the lowest cost per mile, even with the cellulosic premium.

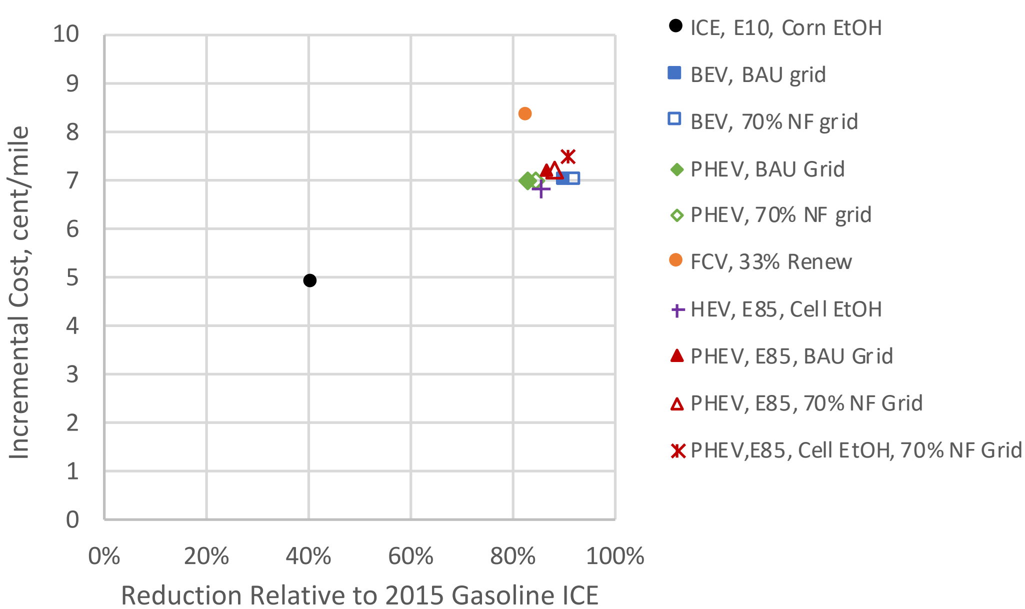


Figure 4-11. California LDA incremental costs and GHG reduction in 2050

Figure 4-12 through Figure 4-14 provide the corresponding results for California LDTs. Consistent with the U.S. analysis, the California LDT scenarios consider maximum penetration of BEVs, PHEVs, E85 PHEVs, E85 HEVs, and CNG vehicles using high levels of RNG. Only BEVs achieve the 2050 goal without reducing fuel carbon intensity. No E10 PHEVs meet the goal, but the dedicated E85 PHEV does, if it is fueled with either advanced ethanol or a 70% non-fossil grid. Non-electrified options that meet the CA 2050 goal include CNG vehicles using RNG, and E85 HEV using advanced ethanol. The CNG-RNG and FCV scenarios have the highest cost. The BEV scenarios have the lowest cost and highest reduction.

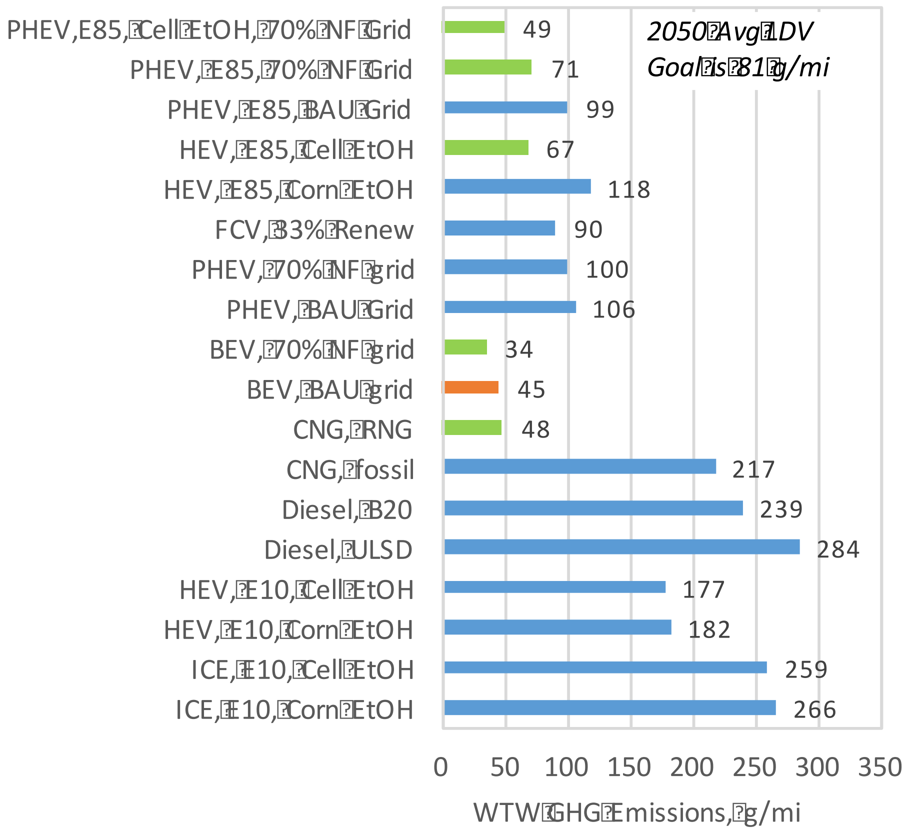


Figure 4-12. California LDT emissions in 2050 with improved fuel economy 2025-2050

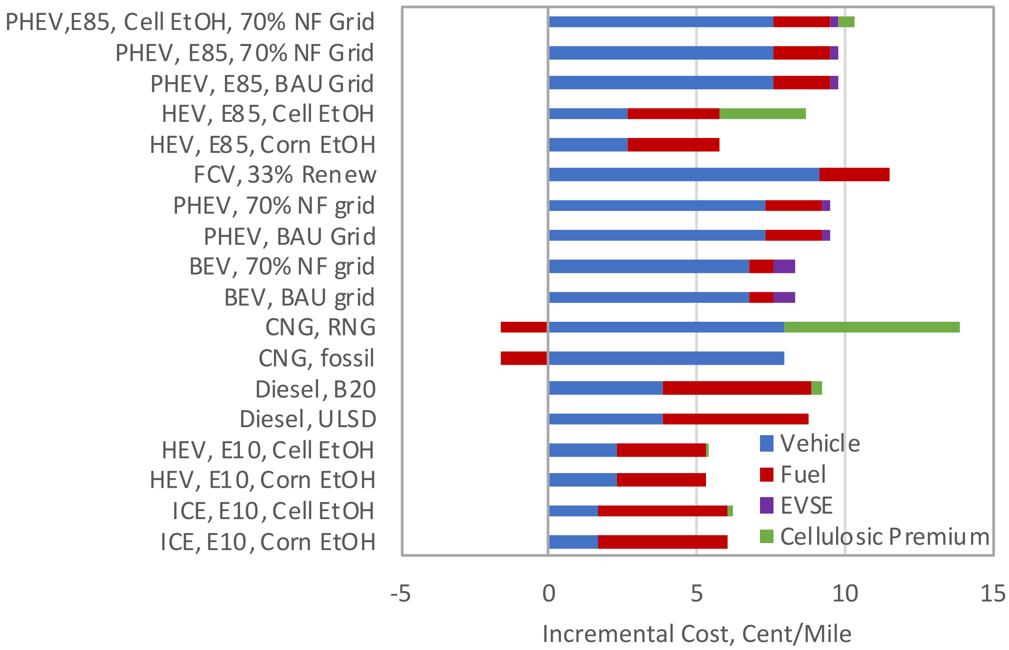


Figure 4-13. California LDT incremental costs in 2050

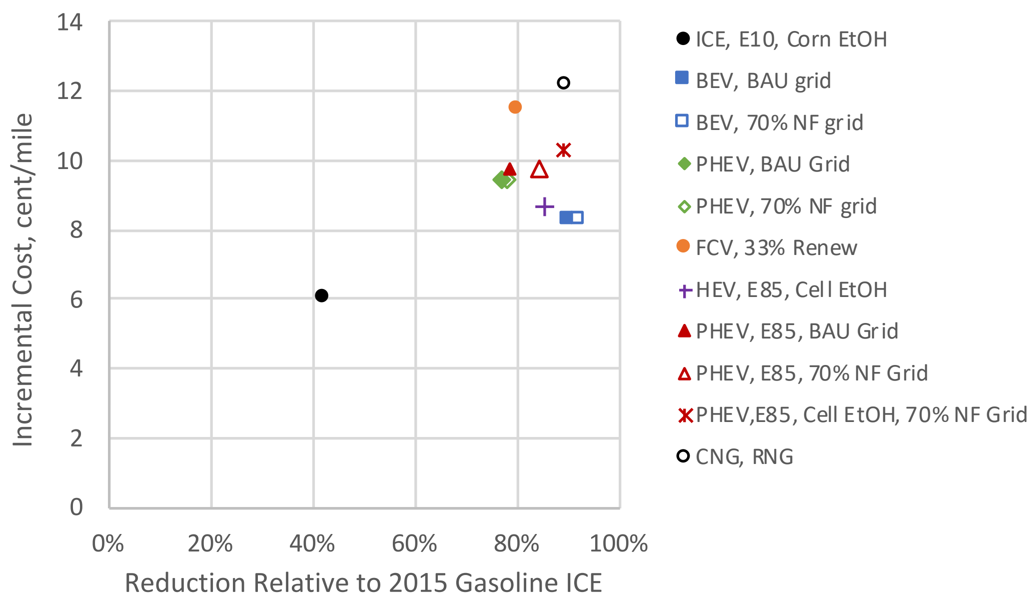


Figure 4-14. California LDT incremental costs and GHG reduction in 2050

5. Scenario Analysis – U.S. Fleet

The objective of this U.S. scenario analysis is to determine if an 80% GHG emission reduction from 2005 levels is possible for the light-duty transportation sector, and if so, what is needed in terms of advanced vehicle technology sales and sales of fuels needed by these technologies. To answer these questions, scenarios were constructed based on technology penetration constraints that maximized the population of the cleanest vehicle/fuel combinations (GHG emissions meeting or exceeding the overall light duty fleet 2050 emissions goal of 86 g CO_2 equivalent/mile). The midterm report by EPA, ARB and NHSTA indicated that the 2025 standards could largely be achieved with advanced gasoline ICE vehicles. As a result, the GHG reduction scenarios assume that the new car sales through 2025 are the same as the BAU case (mainly gasoline ICE vehicles). To meet the 80% GHG reduction goal, GHG reduction scenarios were developed with increased levels of electrification and/or low-CI fuels. The following sections describe the scenarios evaluated, the results of the analysis, and the results of sensitivity tests.

5.1 Scenario Definition

There are four main scenarios that were compared against business as usual—one for each promising vehicle technology identified in Chapter 4 above (BEV, E10 PHEV, E85 PHEV, E85 HEV)[60]. While total vehicle sales for the scenarios remain the same as in the BAU case, each scenario increases the market share of one of the four key technologies at the expense of gasoline ICE vehicles. Maintaining total fleet population and VMT assumptions, the altered technology market shares result in changes in fuel consumption quantity and type, lowering overall GHG emissions. Table 5-1 provides the modified vehicle market share values in 2050 for each scenario. The following guidelines were used to adjust new vehicle market shares:

- To fairly compare the scenarios, alternative technologies replaced gasoline ICE vehicle market shares. Gasoline ICE market share decreased to 4.3% for LDA and 4.6% for LDT by 2050 in all scenarios.
- All other technology shares were maintained at BAU levels unless noted
- Because BEV market share is potentially limited by refueling infrastructure limitations[61], it is assumed that maximum possible BEV market share is 70% for LDA, and maximum PHEV market share is 80% for LDA.
- Because electrification is not currently compatible with towing requirements of large LDTs and SUVs, maximum LDT market share for BEVs and PHEVs is set at 45%. To maximize LDT alternative vehicles, PHEVs and BEVs were supplemented with E85 HEVs or CNGVs.

[60] Hydrogen FCVs are also a possible low emission vehicle strategy but were not included in this study.
[61] In addition to being limited by homes with EVSE access, even with new public charging infrastructure penetration is still not expected to achieve more than 70% due to BEV attributes that will continue to lag other vehicle technologies.

- E85 HEVs are assumed to have a faster ramp up to market penetration than plug-in options because incremental price is lower, range is not an issue, and charging capability is not required.

Table 5-1. New vehicle market share assumptions for U.S. analysis scenarios

Scenario	2050 LDA Market Share	2050 LDT Market Share
BAU	85% Gasoline ICE 1% Diesel 6% HEV 3% PHEV 4% BEV 1% H2 FCV	94% Gasoline ICE 2% Diesel 1% HEV 1% PHEV 1% BEV 1% FCV
1. Max BEV	70% BEV 15% E85 HEV 4.3% Gasoline ICE All others BAU	45% BEV 45% E85 HEV 4.6% Gasoline ICE All others BAU
2a. Max PHEV/E85 HEV	80% E10 PHEV 4.4% E85 HEV 4.3% Gasoline ICE All others BAU	45% E10 PHEV 45% E85 HEV 4.6% Gasoline ICE All others BAU
2b. Max PHEV/CNG	Same as 2a	45% PHEV 46% CNG 4.6% Gasoline ICE All others BAU
3. Max E85 PHEV	81% E85 PHEV 4.3% Gasoline ICE All others BAU	45% E85 PHEV 45% E85 HEV 4.6% Gasoline ICE All others BAU
4. Max E85 HEV	81% E85 HEV 4.3% Gasoline ICE All others BAU	90% E85 HEV 4.6% Gasoline ICE All others BAU

Figure 5-1 and Figure 5-2 illustrate the assumed LDA and LDT new vehicle market shares for Scenario 1 (Max BEV). Note that BEVs are supplemented with dedicated E85 HEV sales due to the maximum penetration limits (70% LDA and 45% LDT) established for BEVs. In addition, note the slower market share ramp rate for BEVs relative to HEVs. The effect is more evident for LDTs, where both technologies rise to a maximum 45% market share, but at different trajectories. Gasoline ICE market shares increase in the near-term as FFVs are phased out.[62] Please refer to Appendix D for similar new vehicle market share figures for Scenarios 2-4.

[62] Beginning in model year (MY) 2016, EPA's light-duty vehicle GHG program no longer allows FFV credits, but instead the GHG compliance values of an FFV must be based on actual emissions performance of the FFV on both gasoline and the alternative fuel, weighted by the EPA's assessment of the actual ethanol used.

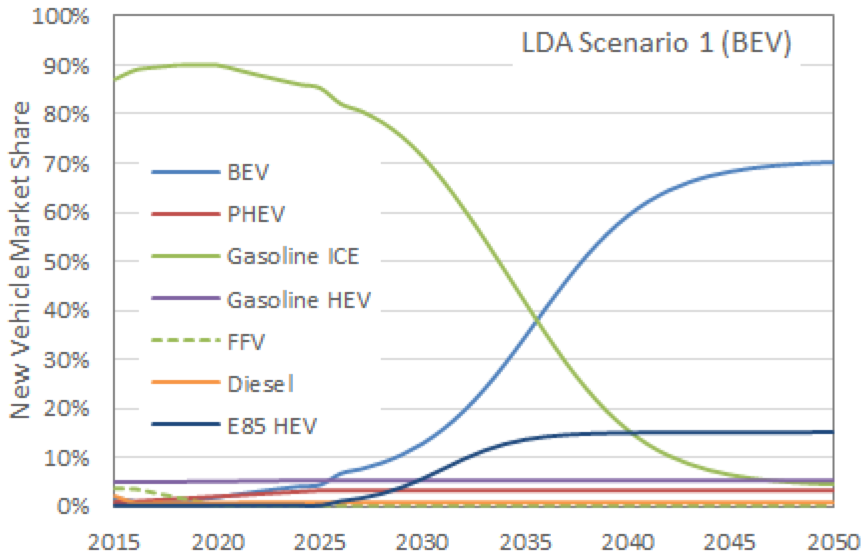


Figure 5-1. LDA assumed new vehicle market shares for Scenario 1

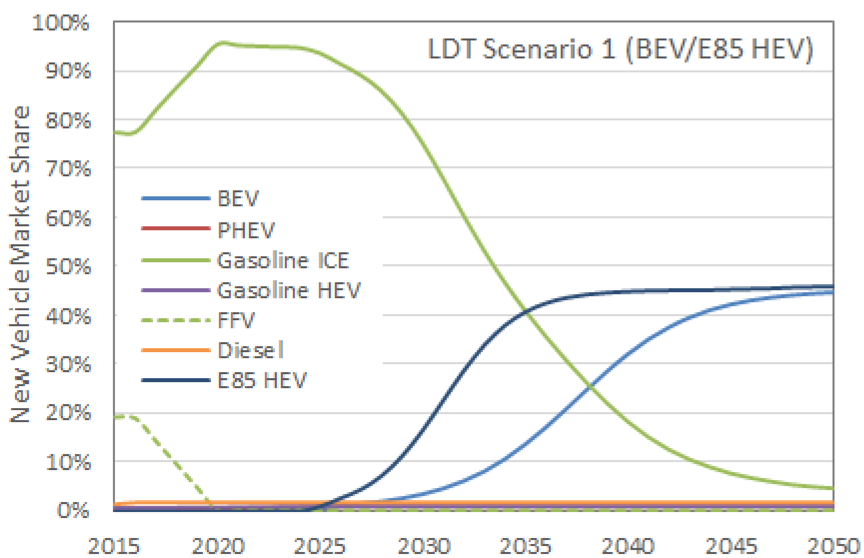


Figure 5-2. LDT assumed new vehicle market shares for Scenario 1

The scenarios were also evaluated with a base (or reference) fuel case, as well as low carbon-intensity fuels:

- Scenarios 1-3 (plug-in technologies) were evaluated with two sets of CI values: AEO2016 reference case grid mix and 70% non-fossil grid mix.
- All scenarios were evaluated with the base case ethanol mix and a low-CI mix (see Section 2.6).

The GHG reduction scenarios are unlikely to be realized without regulatory drivers such as continued CAFE pressure and/or a federal ZEV Mandate. It is therefore assumed for the GHG reduction scenarios that auto manufacturers will continue improving fuel economy of existing technologies for 2025-2050. We have referred to this scenario as BAU with continuing fuel economy improvements post 2025 as described in Section 2.5. As a reminder, the BAU case assumes no improvement in fuel economy for 2025-2050.

Finally, due to uncertainty of future model inputs, the following extra cases were considered:

- To evaluate the impact of repealing the Clean Power Plan, a case was run for Scenario 1 and the BAU using CI values reflecting the AEO2016 grid mix side case without the Clean Power Plan.
- Scenario 2b was evaluated with base case RNG shares and a high RNG mix (Please see Section 2.6).

In addition, Section 5.7 describes sensitivity analysis for electricity prices, fuel production costs, PHEV use of electricity, and BEV fuel economy.

5.2 Fuel Volumes

A key metric of this analysis is fleet fuel consumption. Projected light-duty fuel use is provided in Figure 5-3. Due to improving fuel economy, U.S. BAU fuel use declines steadily through 2030 as more efficient vehicles replace older models. After 2030, despite increasing vehicle population and VMT per vehicle, a projected shift from LDT to LDA keeps fuel consumption fairly constant. For the BAU case with continuing fuel economy improvement (but no change in vehicle technology market share), fuel consumption continues to decrease through 2050 at about half the rate from 2015-2030.

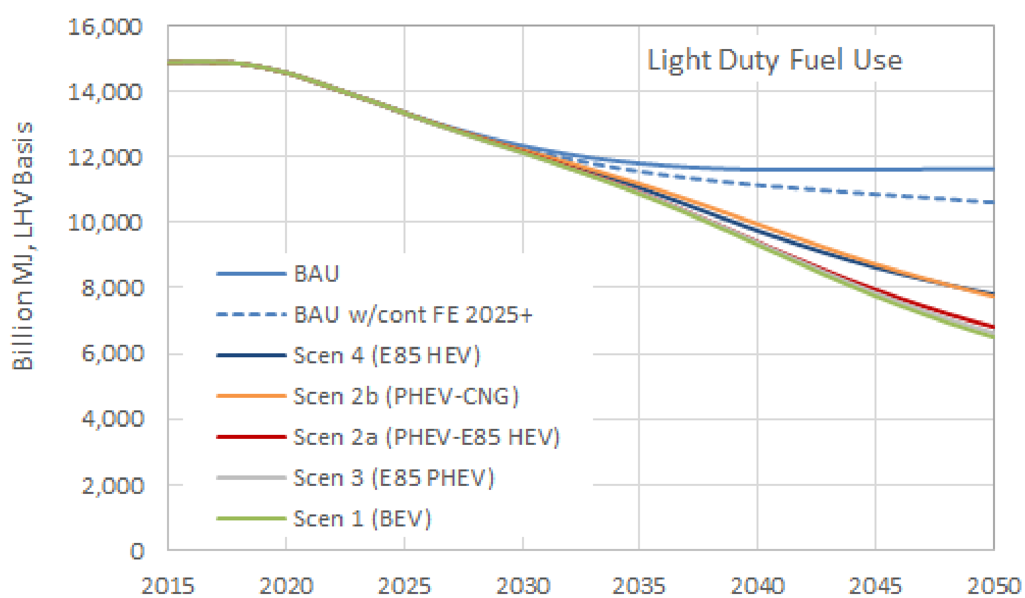


Figure 5-3. Projected U.S. total light-duty fuel use.

The maximum electrification scenarios (1, 2a, 3) all result in a ~55% reduction in fuel use between 2015 and 2050. Electric vehicles are approximately 3 times more fuel efficient than conventional vehicles. Scenario 4, the non-electrification dominant scenario yields a 47% reduction in fuel use, like scenario 2b which consists of PHEVs and CNG vehicles. Scenario 2b's average fuel economy (PHEV/CNG) is like scenario 4's HEV fuel economy. The BAU cases reduce light-duty petroleum use 24-30%, while the alternative scenarios decrease petroleum consumption 71-78% (Figure 5-4).

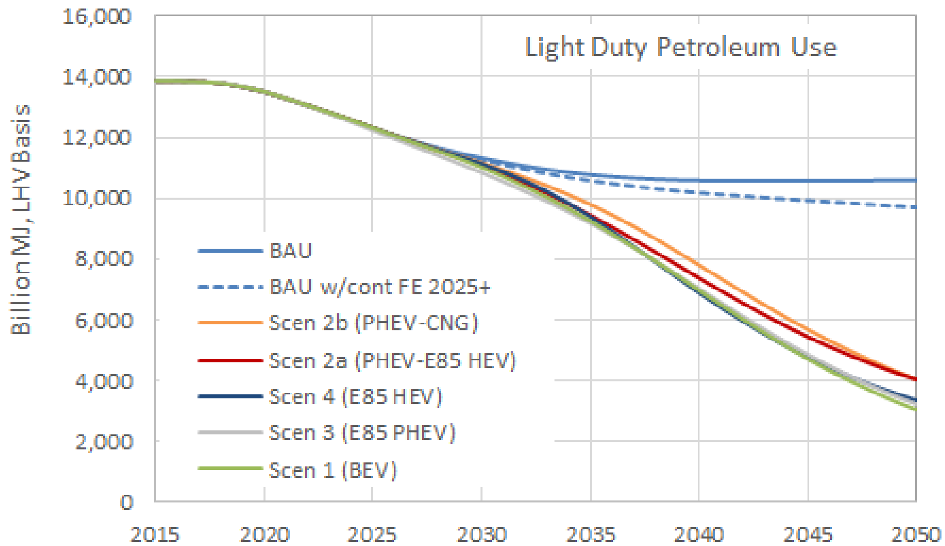


Figure 5-4. Projected U.S. light-duty petroleum consumption

Figure 5-5 illustrates the projected total light-duty ethanol consumption for each of the scenarios. The total renewable fuel volume mandated for 2022 by the RFS is 36 BGY and is shown for reference. Although the mandated volume includes all renewable fuels, the lion's share to date has been ethanol. For example, the total renewable fuel volume for 2015 was set just under 17 BGY[63]; of this, nearly 15 BGY was ethanol (mainly corn).[64]

For BAU, ethanol use is expected to decrease 23% from 2015 levels by 2050. In BAU with continued fuel economy improvements (dashed line in figure), total ethanol use is projected to decrease by 29% to under 9 BGY in 2050, due to the phase out of FFVs and higher fuel economy. Scenario 2b decreases ethanol consumption by 60% from 2015 levels due to the high market share of light truck CNG vehicles. Scenarios 1 and 2a increase ethanol use by 81% and 62%, due to moderate sales of E85 HEVs. Scenario 1 has more light duty auto E85 HEVs because the maximum penetration of BEVs was set at 70%, compared to the maximum PHEV penetration of 80% in Scenario 2a. Scenario 3 (E85 PHEVs) more than doubles light-duty ethanol use compared to current levels while the non-electrification Scenario 4 (E85 HEV) results in nearly 53 BGY of ethanol use by 2050.

[63] https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2014-2015-and-2016-and-biomass-based

[64] We estimate about 14 BGY for the light duty fleet. The 15 BGY used in 2015 includes medium- and heavy-duty use.

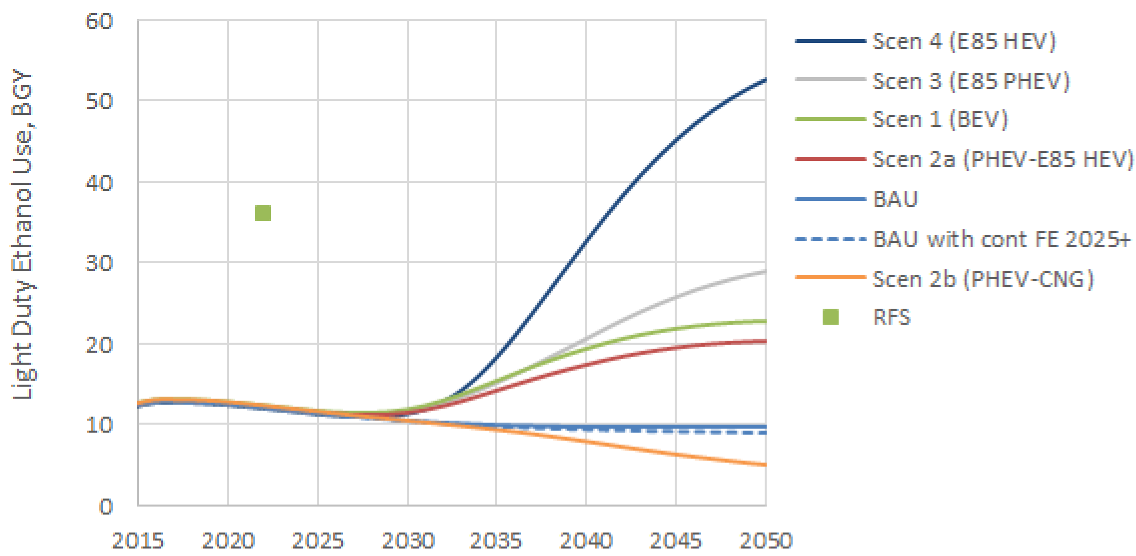


Figure 5-5. Projected U.S. light-duty total ethanol use for BAU and scenarios

Ethanol consumption on the order of 50 BGY would be a significant shift in light-duty fuel use. The original RFS assumed use of up to 15 BGY of conventional corn ethanol for 2015-2022 (Figure 1-3), which required a decade of exponential growth for the corn ethanol industry to achieve. Whether an additional 40 BGY of corn ethanol could economically be produced is unlikely. On the other hand, recent DOE estimates from the Billion Ton Update[65] indicate that domestic cellulosic feedstocks are sufficient to produce the necessary ethanol. The study states that 1.2 billion dry tons of biomass (forest, agricultural residue and waste) are recoverable at a moderate price of $60 per ton. With a yield of 85 gal/dry ton[66], this corresponds to potential cellulosic ethanol production of 100 BGY. It is also possible to produce ethanol from natural gas; from a carbon standpoint this is not a preferable option, but it may represent an economic alternative to renewable ethanol.

Projected cellulosic ethanol consumption (a subset of total ethanol) is shown in Figure 5-6. The BAU case and all base scenarios require the same amount of cellulosic ethanol – up to 0.5 BGY. In contrast, the low-CI scenarios assume that ~ 50% of ethanol is cellulosic. Scenario 4 with low-CI ethanol requires 26.4 BGY. As discussed above, there are ample cellulosic feedstocks for this level of domestic production according to the Billion Ton Update. However, the economic and technical feasibility of such large-scale production remains highly uncertain. Decades of R&D have thus far failed to achieve the necessary breakthrough(s).

[65] U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN.
[66] Slightly more conservative than the GREET yield assumption of 90 gal per dry ton.

Scenario 2b assumes a large penetration CNG light-duty trucks, which requires 12.8 BGY of RNG. Combining this with estimated MD and HD RNG use results in a total of 16 BGY—just under what is thought to be the commercial potential[34].

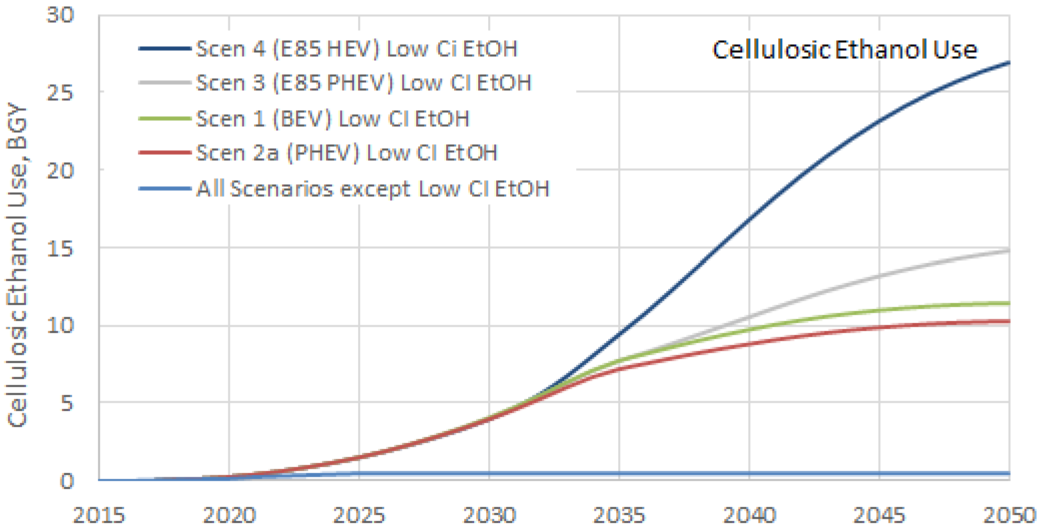


Figure 5-6. Projected light-duty cellulosic ethanol volumes

5.3 GHG Emission Reductions

GHG emissions as a function of time for BAU and each GHG reduction scenario are illustrated in Figure 5-7 (Light Auto) and Figure 5-8 (Light Truck). For all cases, emissions decrease steadily through 2030 as CAFE standards become more stringent and older vehicles retire and are replaced with newer more efficient vehicles. For light autos, BAU emissions start increasing again after 2035 while light truck emissions decrease as auto sales increase at the expense of trucks (see Figure 2-2). For LDA and LDT, the scenarios without increased use of low-CI fuels (solid lines in the graphs) yield similar GHG emissions by 2050 except for light truck Scenario 2b (PHEV+CNG, the orange line). CNG vehicles with fossil natural gas have higher emissions than E85 HEVs, so Scenario 2b has higher emissions than its counterpart, Scenario 2a with E85 HEVs. For autos and trucks, Scenario 1 (BEV+E85 HEV) and Scenario 3 (E85 PHEV+E85 HEV) with low-CI fuels have lower emissions than Scenario 2a (E10 PHEV+E85 HEV) and Scenario 4 (E85 HEV). For autos, the low-CI version of Scenario 2 has lower emissions than the low-CI version of Scenario 4, while for trucks, the low-CI Scenarios 2a and 4 yield similar emissions. This is because light trucks have a lower market share of PHEVs than light autos.

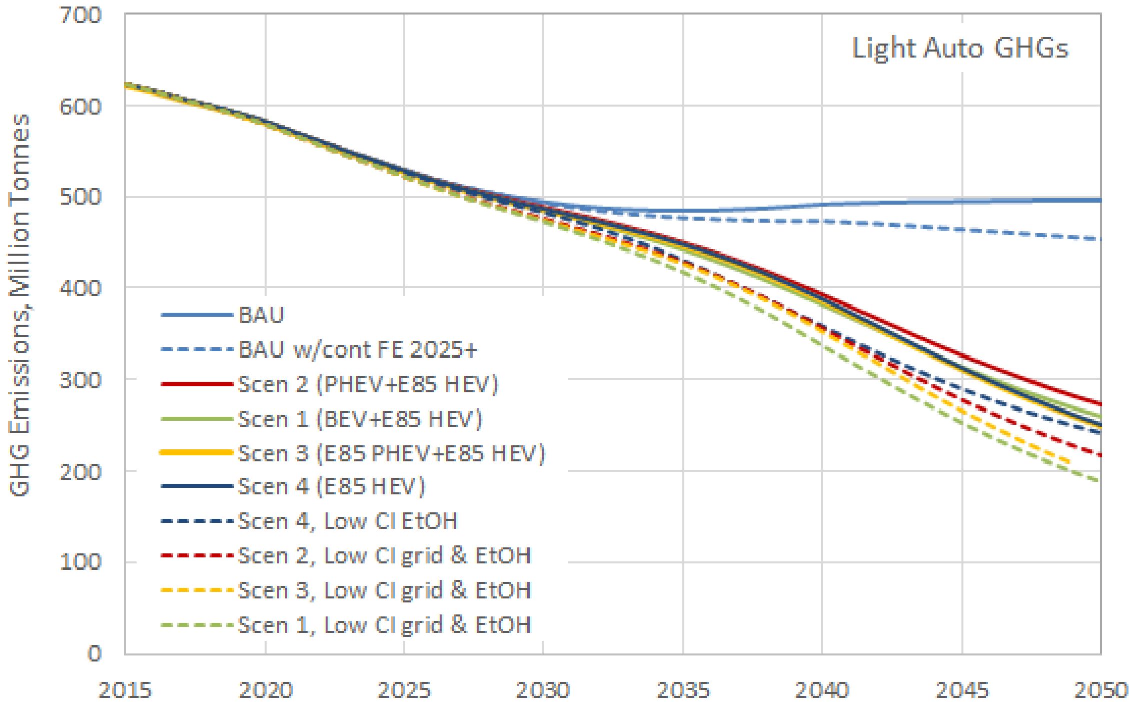


Figure 5-7. Projected U.S. LDA GHG emissions

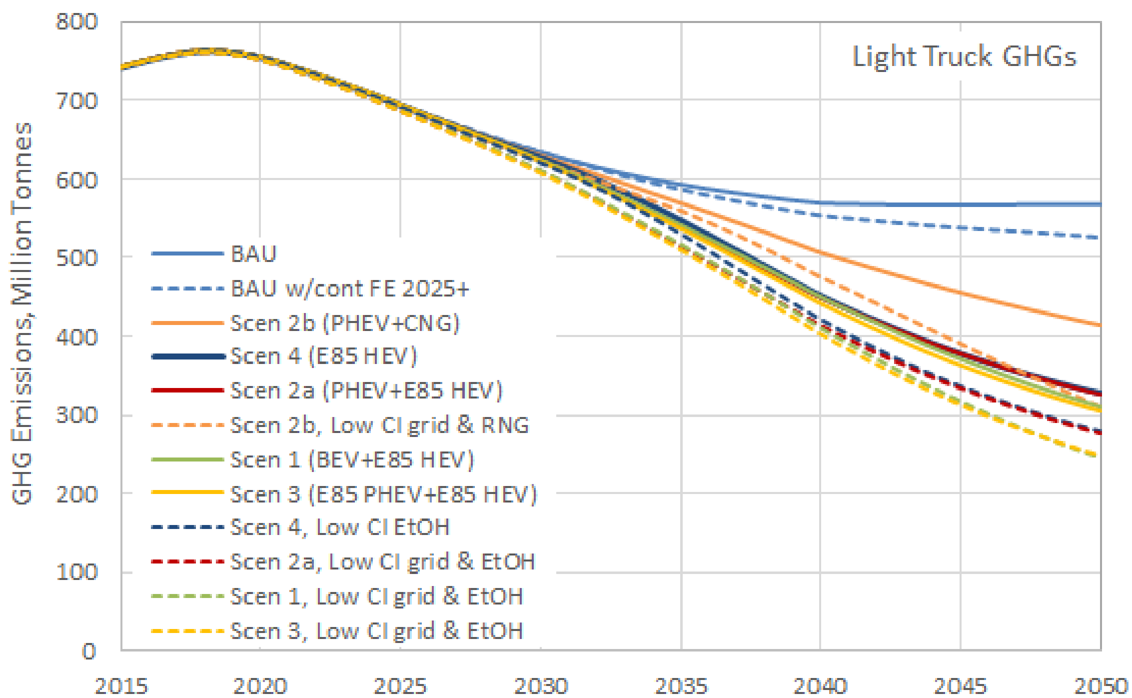


Figure 5-8. Projected U.S. LDT GHG emissions

As discussed in Section 4.1, several individual vehicle and fuel technology combinations achieve the 2050 goal of 80% GHG reduction. However, as shown in Figure 5-9, even with aggressive market share assumptions of the cleanest technologies, none of the scenarios achieves the combined light-duty 2050 goal. More time is needed for older vehicles to retire and be replaced with more efficient less carbon intensive options, or the cleaner options must be introduced faster. All the base scenarios (solid lines) yield similar GHG emission levels in 2050. Of the low-CI scenarios (dashed lines), the BEV and E85 PHEV options reduce GHG emissions more than the PHEV and E85 HEV scenarios.

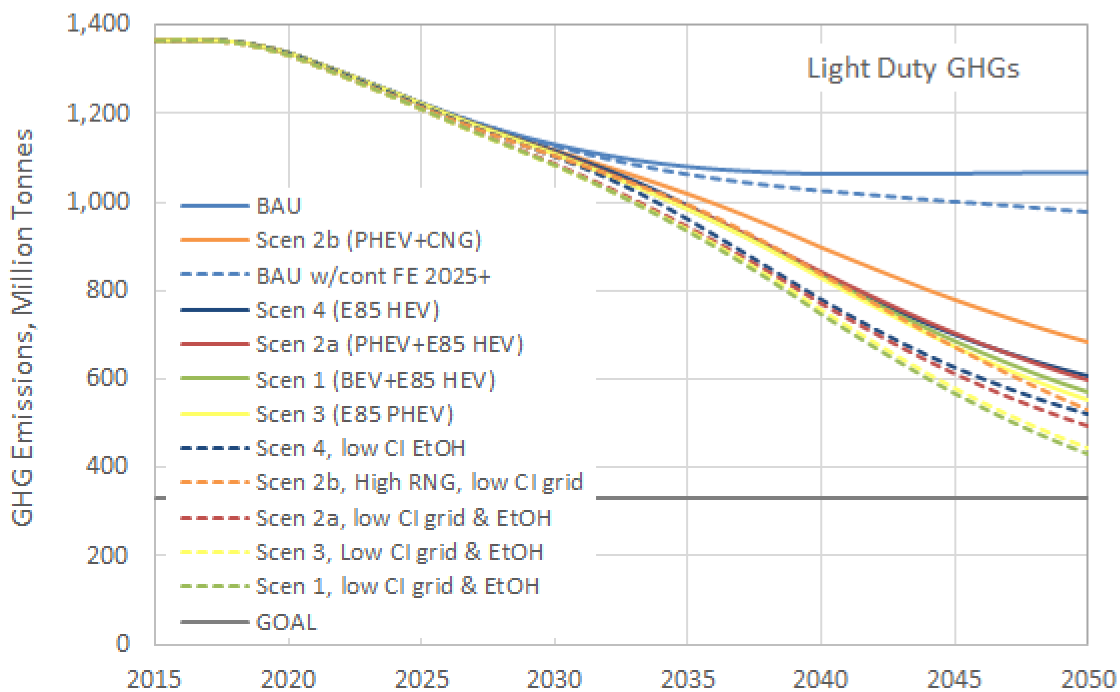


Figure 5-9. Projected U.S. LDA+LDT GHG emissions

Because GHGs accumulate in the atmosphere, projected cumulative reductions are a better indicator of climate impact than GHG emissions in 2050.[67] For each scenario (including BAU with improved fuel economy for 2025-2050), the running total of annual GHG reductions relative to BAU are calculated to represent cumulative reductions over time. Figure 5-10 shows the cumulative GHG reductions for each scenario. With moderately increasing fuel economy beyond 2025 and no change in vehicle technology market shares compared to BAU, 1 billion tonnes of GHGs can be abated by 2050. The alternative scenarios with conventional fuel abate up to 5 billion tonnes of GHGs, while the low-CI versions abate up to 7 billion tonnes.

[67] The IPCC relates cumulative GHG emissions to atmospheric concentrations of CO2 (refer to the IPCC Fifth Assessment Report, Summary for Policy Makers) and "Warming Caused by Cumulative Carbon Emissions Towards the Trillionth Tonne", Nature 458, 1163-1166 (30 April 2009) by Myles Allen et al.

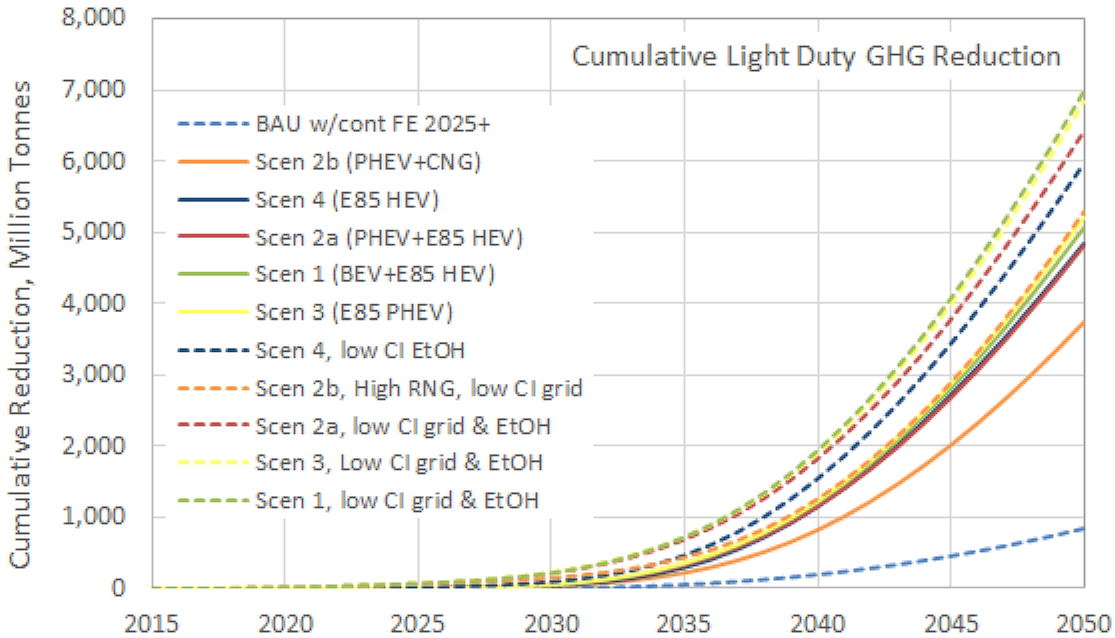


Figure 5-10. Projected U.S. LDA+LDT cumulative GHG reduction relative to BAU

For reference, Figure 5-11 illustrates the composite ethanol carbon intensity value over time for the BAU and low CI cases. The cellulosic content increases to 50% and the CI value decreases 28% relative to the BAU in 2050, but by nearly 40% from the 2015 composite value. Similarly, Figure 5-12 summarizes the change in electricity CI and non-fossil content over time. The electricity CI for the 70% non-fossil case is 60% lower than the BAU CI in 2050.

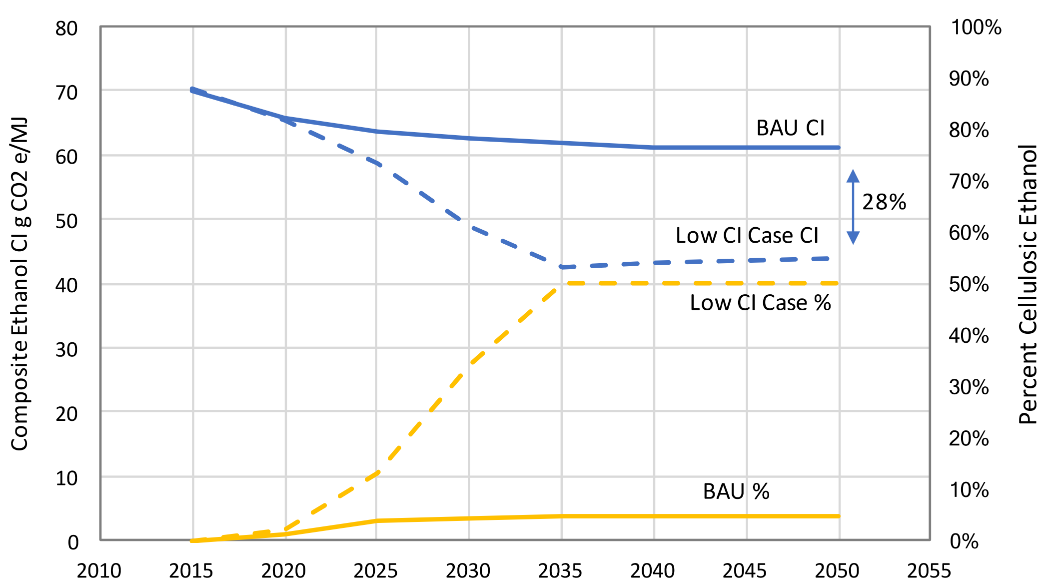


Figure 5-11. Comparison of composite ethanol CI for BAU and low CI case

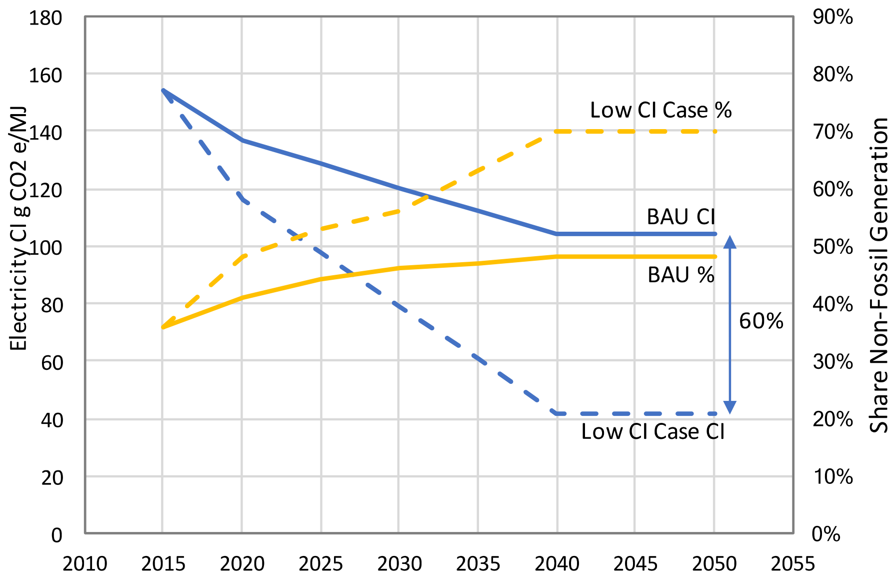


Figure 5-12. Comparison of electricity CI for BAU and low CI case

Figure 5-13 illustrates relative contribution of LDA and LDT to the 2015-2050 cumulative total GHG reductions for each alternative scenario. For Scenario 1 (BEV), the Clean Power Plan reduces GHGs by 460 million tonnes over the analysis period. A low-CI grid for Scenario 1 provides an additional 1340 million tonnes of abatement while its low-CI ethanol abates an additional 590 million tonnes. In the non-electrification scenario (Scenario 4, E85 HEV), low-CI ethanol reduces GHGs by 1200 million tonnes over the analysis period.

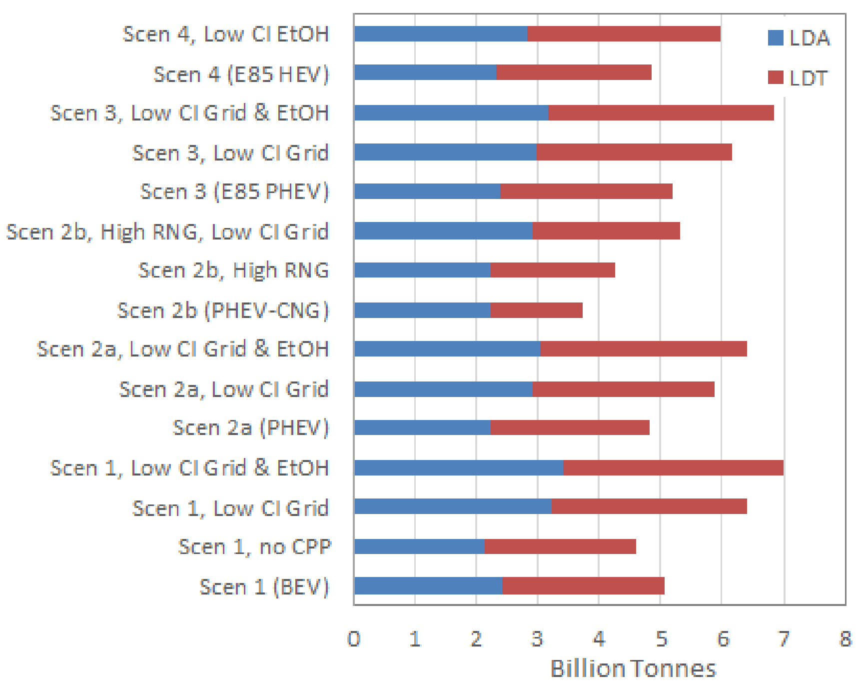


Figure 5-13. Cumulative GHG reductions relative to BAU (2015-2050)

5.4 Change in Fuel Costs

Changes in spending on fuel are provided in Figure 5-14 and Table 5-2. All scenarios reduce costs., Electrification options provide more fuel savings than the E85 HEV scenario because electric vehicles are ~ 3 times more efficient than an ICE. Scenarios with more cellulosic ethanol and RNG use have higher production costs. These higher production costs are assumed to be captured by increased RIN costs and tax credits. The tax credits for cellulosic ethanol, biodiesel and renewable diesel are assumed to expire in 2025 and therefore have minimal impact on results. However, the RIN premium for cellulosic ethanol is assumed to stay at today's value of $1 per gallon higher than conventional ethanol throughout the analysis period. For the low-CI version of Scenario 4 (E85 HEV) with significant cellulosic ethanol use, production costs could be expected to decrease through learning and economies of scale. A separate sensitivity case was not run with lower RIN costs, but the conventional ethanol version of Scenario 4 can be used as a least cost estimate (if cellulosic ethanol production is never less expensive than corn ethanol production).

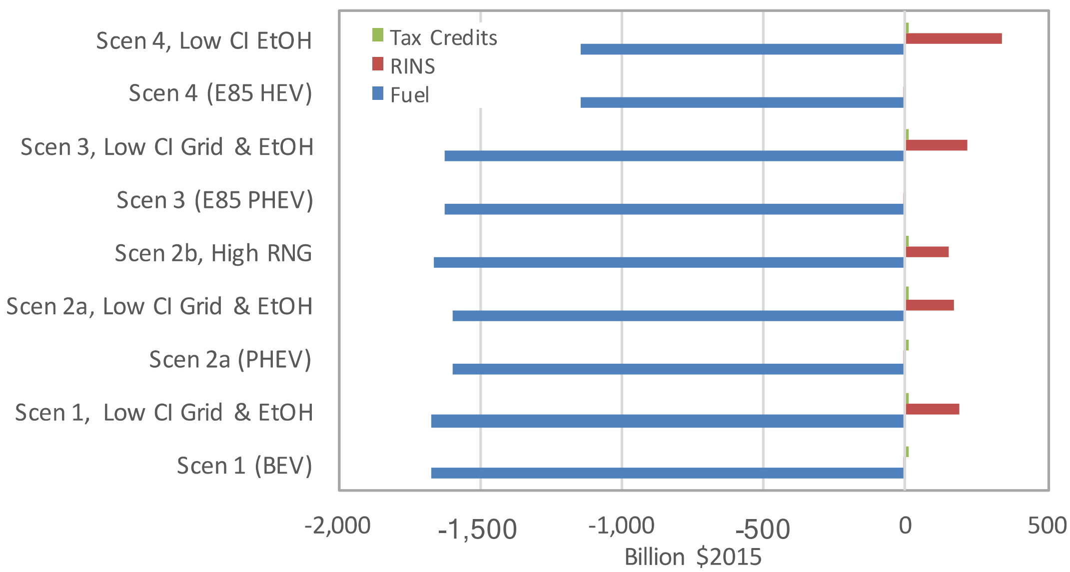


Figure 5-14. Change in cumulative fuel spending relative to BAU (2015-2050)

Table 5-2. Summary of cumulative (2015-2050) fuel costs relative to BAU, Billion $2015

	Change in Fuel Spending	Cellulosic Premium	Change in Tax Credits	Net Change in Fuel Costs
Scen 1 (BEV)	-1,671	0	0	-1,671
Scen 1, Low CI Grid & EtOH	-1,671	190	3	-1,478
Scen 2a (PHEV)	-1597	0	0	-1,597
Scen 2a, Low CI Grid & EtOH	-1597	173	3	-1,421
Scen 2b, High RNG	-1,664	147	0	-1,517
Scen 3 (E85 PHEV)	-1,624	0	0	-1,624
Scen 3, Low CI Grid & EtOH	-1,624	215	3	-1,406
Scen 4 (E85 HEV)	-1,142	0	0	-1,142
Scen 4, Low CI EtOH	-1,142	342	3	-797

5.5 Change in Vehicle and EVSE Spending

The cumulative increase in vehicle spending relative to BAU is provided in Figure 5-15. The non-electrification Scenario 4 has the lowest incremental vehicle costs. The rest of the scenarios have higher costs, with Scenario 2b the most expensive because CNG trucks have a higher incremental cost than E85 HEVs. The income tax credit for plug-in vehicles expires when 200,000 PEVs per manufacturer are sold. Assuming 15 manufacturers, the tax credits will expire once 3 million vehicles have sold. This threshold is crossed in 2018. Since all scenarios have the same PEV sales up to 2025, the tax credit does not impact scenario vehicle costs. Individual state rebates for 2025-2050 were not considered here.

The change in cumulative spending on residential EV charging equipment relative to the BAU case is provided in Figure 5-16. Scenario 1 incurs nearly three times the EVSE costs of Scenarios 2 and 3 while Scenario 4 has the same EVSE costs as BAU.

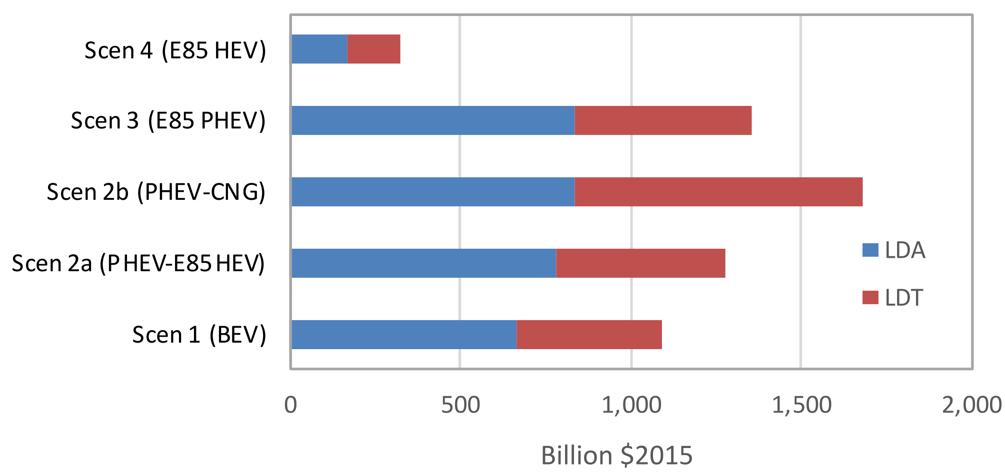


Figure 5-15. Change in cumulative vehicle spending relative to BAU (2015-2050)

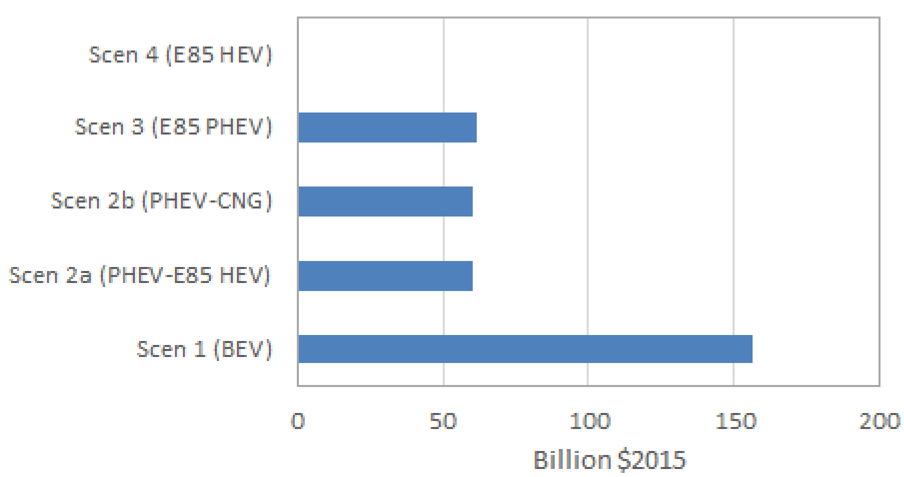


Figure 5-16. Change in cumulative EVSE spending relative to BAU (2015-2050)

5.6 Cost Effectiveness

To compare the scenarios, overall cumulative costs (not discounted) are summarized in Figure 5-17 and Table 5-3. All scenarios provide substantial fuel cost savings relative to the BAU case that are decreased by higher vehicle and EVSE costs. Scenario 4 (E85 HEV) cumulative vehicle costs are 4 to 5 times lower than the other scenarios, resulting in the lowest net costs of all scenarios though the base BEV scenario (Scenario 1) has similar net cost to the E85 scenario with low CI ethanol. All scenarios except Scenario 2b (PHEV/CNG) and Scenario 3 (E85 PHEV with low CI ethanol) provide net cumulative savings; the low-CI ethanol versions of these scenarios are pricier due to higher ethanol costs. Scenario 2b has significant fuel cost savings (due to low CNG prices relative to gasoline and ethanol), but not enough to offset higher vehicle costs. The low-CI, high RNG version of Scenario 2b substantially increases fuel costs, yielding the highest net cost of all the scenarios.

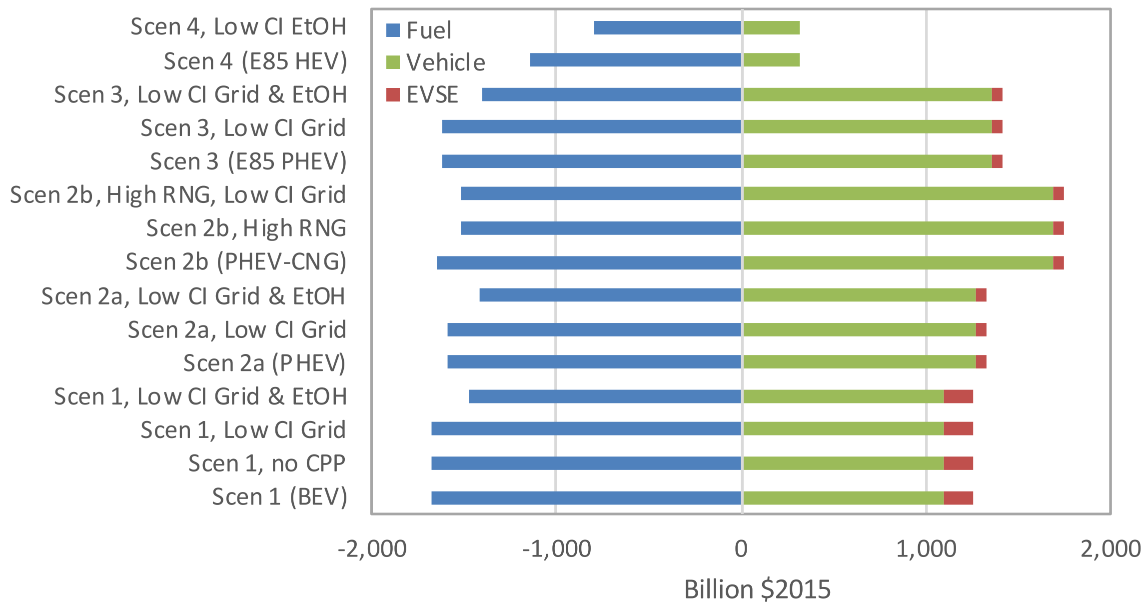


Figure 5-17. Change in U.S. light-duty cumulative costs relative to BAU (2015-2050)

Table 5-3. Summary of cumulative (2015-2050) U.S. light-duty costs relative to BAU

Billion $2015	Fuel Spending	Vehicle Spending	EVSE (Chargers)	Cumulative Cost
Scen 1 (BEV)	-1,671	1,094	156	-421
Scen 1, Low CI Grid & EtOH	-1,478	1,094	156	-228
Scen 2a (PHEV-E85 HEV)	-1,597	1,275	60	-262
Scen 2a, Low CI Grid & EtOH	-1,421	1,275	60	-85
Scen 2b (PHEV-CNG)	-1,645	1,684	60	99
Scen 2b, High RNG	-1,517	1,684	60	228
Scen 2b, High RNG, Low CI Grid	-1,517	1,684	60	228
Scen 3 (E85 PHEV)	-1,624	1,352	62	-211
Scen 3, Low CI Grid & EtOH	-1,406	1,352	62	8
Scen 4 (E85 HEV)	-1,142	322	0	-820
Scen 4, Low CI EtOH	-797	322	0	-470

Cost effectiveness, defined as cumulative costs relative to BAU divided by cumulative GHG reductions relative to BAU is presented in Figure 5-18 and summarized in Table 5-4. Cost effectiveness ranges from a savings of $173 per tonne for Scenario 4 to a cost of $55 per tonne for Scenario 2b with high RNG use. For context, carbon credits cost about 15 $/tonne in the California market[68] and Synapse Energy[69] has forecast credit prices to increase from a 2016 value of $20 per tonne to $80 per tonne in 2050. All scenarios except Scenario 2b and Scenario 3 with cellulosic ethanol have negative cost effectiveness (a cost saving).

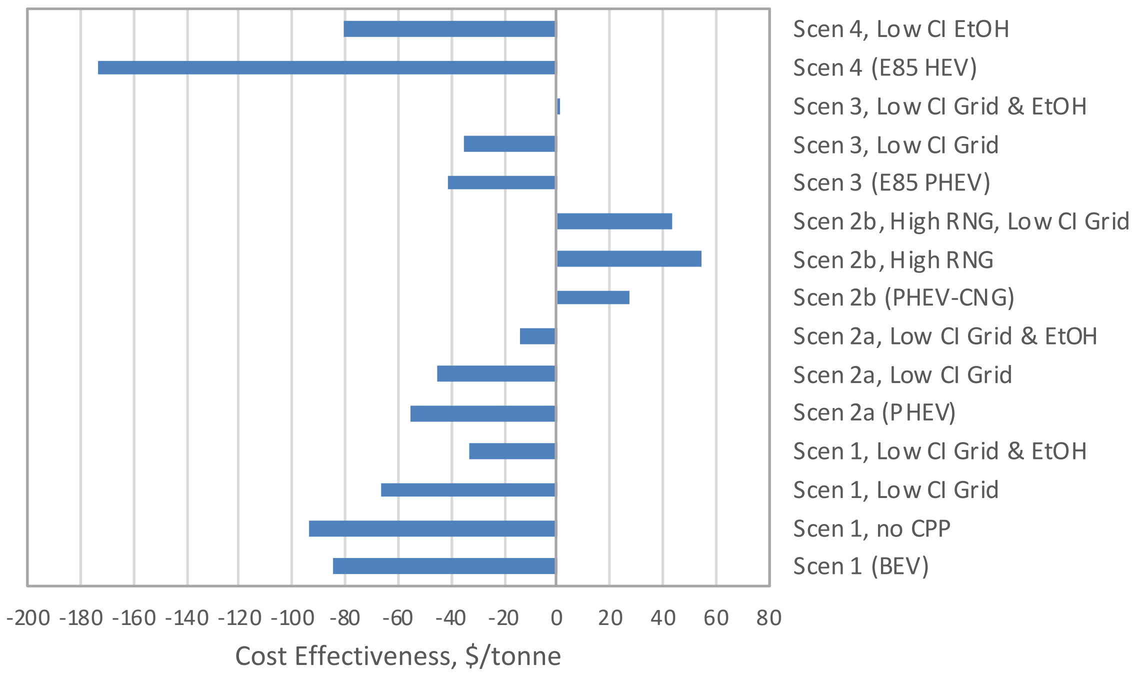


Figure 5-18. U.S. Light-duty cost effectiveness (cumulative cost/cumulative reduction)

Table 5-4. Summary of U.S. analysis cost effectiveness

	Base Scenarios		Low-CI Options	
	Cost Effectiveness ($/tonne)	Cumulative Reduction (Billion tonnes)	Cost Effectiveness ($/tonne)	Cumulative Reduction (Billion tonnes)
Scen 1 (BEV)	-85	5.0	-33	6.9
Scen 2a (PHEV/E85 HEV)	-55	4.7	-13	6.3
Scen 2b (PHEV/CNG)	27	3.6	55	4.2
Scen 3 (E85 PHEV/E85 HEV)	-41	5.1	1	6.7
Scen 4 (E85 HEV)	-173	4.7	-81	5.9

[68] California Carbon Dashboard, http://calcarbondash.org/

[69] Spring 2016 National Carbon Dioxide Price Forecast, Synapse Energy Economics, Inc.

Cumulative cost is plotted as a function of GHG reduction in Figure 5-19. Scenario 4 (E85 HEV) with conventional ethanol (– symbol in the figure) is an interesting case since it provides modest GHG reduction at a significant cost savings relative to the BAU scenario. Consumer spending on vehicles is much lower than other scenarios since it does not rely on electrification. It does, however, require ethanol volumes (please refer to Figure 5-5) of more than 50 BGY, more than three times current consumption levels. While this scenario has minimal vehicle technology risk, it carries risk in terms of ethanol supply.

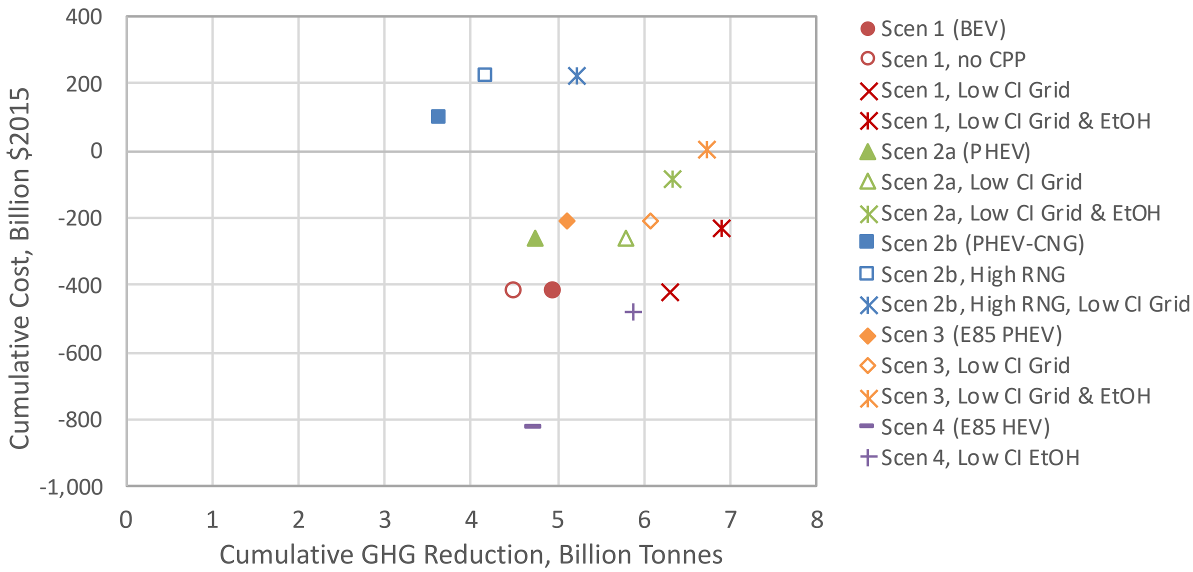


Figure 5-19. Cumulative cost vs cumulative GHG reduction for U.S. light-duty fleet

Scenario 4 with cellulosic ethanol (+ symbol) provides 26% more GHG reduction than its conventional ethanol counterpart, with significantly higher (though still negative) cumulative cost. However, this scenario requires large amounts of cellulosic ethanol, which is a greater risk than Scenario 4 with conventional ethanol. The production cost premium for cellulosic ethanol, approximated here by the difference in current cellulosic RIN price and conventional ethanol RIN price, is assumed to stay at current levels through 2050. However, utilizing significant quantities of cellulosic ethanol would likely reduce production costs due to learning and economies of scale. At the extreme end, the price could decrease to that of corn ethanol, essentially having the same cost as Scenario 4 with conventional ethanol. Even half the production price decrease would significantly increase the economic attractiveness of this scenario, but the technical risk remains.

The scenarios with the next highest cost savings are Scenario 1 and Scenario 1 with a low-CI grid (red symbols). It is assumed here that a low-CI grid has the same retail electricity price as the AEO forecast grid mix. The low-CI grid substantially reduces GHG relative to the AEO grid while rescinding the CPP has a 10% effect in the opposite direction. Due to its emphasis on all-electric vehicles, Scenario 1 is more affected by grid mix than the other scenarios; Scenarios 2 and 3 would experience 5% (0.25 billion tonnes) less cumulative GHG emissions without the CPP. The

low-CI-ethanol BEV scenario increases both costs and GHG reductions. Cellulosic ethanol volumes are markedly lower than Scenario 4 (11 vs 26 BGY), though still significant.
The orange symbols in Figure 5-19 are for Scenario 3 (E85 PHEV), which provides more GHG reduction compared to Scenario 2a (PHEV, green symbols), at a slightly higher cost. The cost difference is due to higher prices for E85 relative to gasoline on an energy basis (Figure 2-26) and slightly higher E85 PHEV vehicle costs relative to the PHEV. Scenario 3 carries the risk of requiring significant ethanol volumes (30 BGY total ethanol for Scenario 3 vs 20 BGY for Scenario 2a).

Finally, Scenario 2b, in which light truck E85 HEVs are replaced by CNG trucks, provides the least cumulative GHG reduction and high costs (due to high CNG vehicle incremental cost). The case with large volumes of RNG provides greater GHG reductions, but at a much higher cost due to high fuel production costs (RINS). The addition of a low-CI grid brings Scenario 2b GHG reductions to a moderate level. CNG vehicles do not appear to be a cost-effective long-term solution compared to other options available.

Table 5-5 ranks the results by assigning a score in each of four categories: cumulative GHG reduction, cumulative incremental cost, vehicle technology risk, and fuel supply risk. Each of these categories is given equal weight to come up with a single score for each scenario. The simplistic scoring assumes that a red rating receives a -1 score, a green rating receives a +1 score and that blue scores are neutral. The scores are summed and normalize to a scale of 1 to 5.

Three options received the “best” overall score of 5: Scenario 1 (BEV) with and without a low CI grid and Scenario 3 (E85 PHEV) with a low-CI grid. The E85 PHEV with low-CI grid provides high GHG reduction at low cost, with medium vehicle technology and fuel supply risk. In contrast, the BEV scenarios provide low to medium GHG reduction at low cost with medium vehicle technology risk and low fuel supply risk.

Eight scenarios received a score of four: Scenario 1 without CPP, Scenario 1 with low CI grid and low CI ethanol, Scenario 2a (all CI options), Scenario 3 base case, and both CI options for Scenario 4. Nearly three quarters of the options considered resulted in a high score; this indicates that there is no preferred solution – electrification and dedicated biofuel vehicles both yield beneficial results.

The scenarios with the lowest scores were Scenario 2b (PHEV+LT CNG) with and without low-CI fuels. Scenario 2b received a 1 because of low GHG reductions and high cost. Scenario 2b with low-CI fuels had better GHG reductions but higher fuel cost and higher fuel supply risk.

Table 5-5. Scenario ranking based on four criteria (5 is best possible score)

	Cumulative GHG Reduction	Cumulative Cost	Vehicle Technology Risk	Fuel Supply Risk	Overall Score
Scen 1 (BEV)	Medium	Low	Medium	Low	5
Scen 1, no CPP	Low	Low	Medium	Low	4
Scen 1, Low CI Grid	High	Low	Medium	Medium	5
Scen 1, Low CI Grid & EtOH	High	Low	Medium	High	4
Scen 2a (PHEV)	Low	Low	Medium	Low	4
Scen 2a, Low CI Grid	Medium	Low	Medium	Medium	4
Scen 2a, Low CI Grid & EtOH	High	Low	Medium	High	4
Scen 2b (PHEV-CNG)	Low	Medium	Medium	Medium	2
Scen 2b, High RNG	Low	High	Medium	High	0
Scen 2b, High RNG, Low-CI Grid	Medium	High	Medium	High	1
Scen 3 (E85 PHEV)	Medium	Low	Medium	Medium	4
Scen 3, Low CI Grid	High	Low	Medium	Medium	5
Scen 3, Low CI Grid & EtOH	High	Medium	Medium	High	3
Scen 4 (E85 HEV)	Low	Low	Low	Medium	4
Scen 4, Low CI EtOH	Medium	Low	Low	High	4

5.7 Sensitivity Tests

The results presented above included some additional cases to determine the effects of grid CI, fuel carbon CI, and CPP implementation. This section provides the results of four more sensitivity tests on cumulative GHG reduction and costs:

- Electricity price
- Cellulosic ethanol production cost (modeled as RIN cost)
- Share of PHEV electric mode VMT (E_{VMT})
- Light auto BEV fuel economy
- BEV incremental vehicle price

The electricity price projection used in the main analysis assumes that consumers pay the same price for electricity regardless of renewable content. Because the impact of a 70% non-fossil grid on retail prices is uncertain, the model was run assuming a 20% increase and a 20% decrease in electricity prices beginning in 2025. Since BEVs are the most impacted by electricity price, this sensitivity test was performed on Scenario 1. Sensitivity of cost effectiveness to electricity prices for Scenario 1 with a low-CI grid is shown by the vertical error bars on the × symbol in Figure 5-20. In this sensitivity analysis, cost effectiveness increases to \$25/tonne and decreases to -\$11/tonne for the electricity prices evaluated, where the increased electricity price evaluated leads to 270% increase in cumulative costs.

The other cost assumption tested is the premium paid for cellulosic ethanol. The base analysis assumes that current fuel production costs (RIN values) persist through the analysis period, resulting in a premium of \$1.00 for cellulosic ethanol over conventional ethanol. The sensitivity test assumed that fuel production costs (D3 RIN price) decreases to a $0.50 premium relative to conventional ethanol by 2025 and remains there through 2050. The test was performed on Scenario 4 (E85 HEV), which is most impacted by cellulosic ethanol production costs.

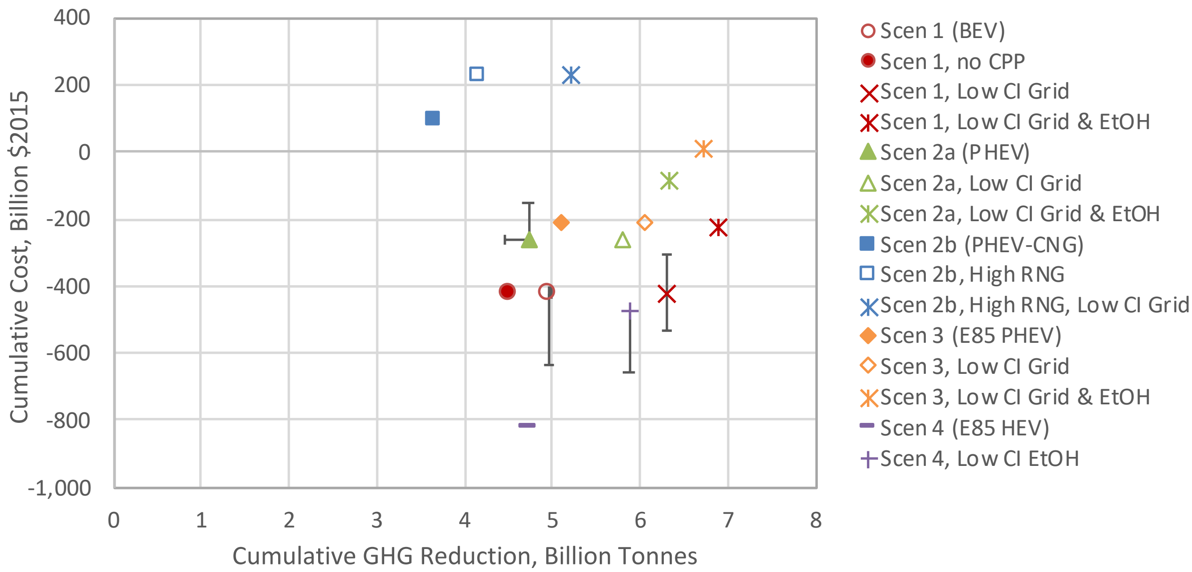


Figure 5-20. Cumulative cost vs reduction with sensitivity case error bars

The impact of higher cellulosic production costs (RIN premiums) on the low-CI E85 HEV scenario is shown by the vertical error bar on the + symbol in Figure 5-20. Reducing the fuel production cost premium relative to conventional ethanol to $0.50 per gallon as of 2025 increases cumulative savings by $180 billion over the analysis period.

The sensitivity of results to the assumed share of miles that PHEVs operate on electricity as opposed to gasoline or E85 was also tested. For the base case, it is assumed that E_{VMT} for light autos is 74.5% and the light truck E_{VMT} share is 55%. For the sensitivity test, we assume the E_{VMT} share drops to 60% and 40% for light autos and light trucks, respectively. This test is performed on Scenario 2a, with the maximum penetration of PHEVs and is compared to a BAU with the same E_{VMT} assumptions. The sensitivity of the PHEV scenario to assumptions regarding E_{VMT} shares is shown by the error bars attached to the ▲ symbol. Decreasing the E_{VMT} share reduces cumulative GHG reduction by 9 percent and increases cumulative costs by nearly $110 billion due to increased use of gasoline.

The sensitivity of results to projected LDA BEV fuel economy is also tested. There was a wide range of projections for LDA fuel economy, and the analysis values selected might be considered conservative (low). Alternative BAU and Scenario 1 cases are run with slightly higher fuel economy values based on the Argonne C2G analysis. The 2025 BEV100 certification value increases from the analysis value of 162 mpgge to the Argonne C2G value of 172 mpgge, a 7% increase. The BEV200 value is increased proportionally. As can be seen by the horizontal error bars attached to the red circle symbol O in Figure 5-20, a 7% change in BEV fuel economy has a very small impact on both cumulative GHG reductions and costs.

The final sensitivity test is BEV battery pack cost. As discussed in Appendix A, the base case BEV costs for 2025 are based on EPA's proposed MTE. The EPA battery pack costs range from 115 to 159 $/kWh. Because many analysts predict that battery pack prices will decrease to the benchmark level of $100 per kWh by 2025, a sensitivity case is performed for $100/kWh battery packs. The resulting incremental vehicle prices for BEV100 and BEV200 LDAs and LDTs decrease by 8% for the light truck BEV200 and up to 24% for the light auto LDA from the base case. As indicated in Figure 5-20, decreasing battery pack prices has a dramatic impact on the BEV scenario cost, approaching the cost of the E85 HEV scenario.

Although these sensitivities were tested on scenarios where they would have maximum impact, it can be concluded that cost effectiveness results are quite sensitive to assumptions regarding fuel price, vehicle incremental price and share of PHEV electric mode miles while cumulative GHG reductions are less sensitive. The results were insensitive to BEV fuel economy assumptions.

5.8 Proposed SAFE Fuel Economy Standard

On August 24, 2018, the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) proposed to amend existing CAFE and GHG standards for passenger cars and light trucks for model years 2021 through 2026. Dubbed the Safer Affordable Fuel Efficient (SAFE) Vehicle proposal, it would essentially freeze the CAFE standard for 2021-2026 at 2020 levels (43.7 mpg for light autos and 31.3 mpg for light trucks). The SAFE analysis modeling by NHTSA maintains these levels through 2030.

To evaluate how this change to fuel economy standards would affect light duty GHG emissions, fuel consumption and consumer costs, a SAFE BAU case was run in which the BAU fuel economy values for each technology were frozen through 2030, shifting the BAU 2021-2040 fuel economy values to 2031-2050. Incremental vehicle costs were also adjusted in a similar fashion. In addition to a SAFE BAU case, two vehicle technology scenarios were considered: SAFE Scenario 1 (Max BEV) and SAFE Scenario 4 (Max E85 HEV). These SAFE scenarios utilize the same vehicle market share introduction rates as their counterparts in the main analysis but shifted ten years to the future.

Figure 5-21 compares the light-duty fleet emissions for the SAFE scenarios to the previous BAU, Scenario 1 (Max BEV) and Scenario 4 (Max E85 HEV). As expected, freezing the CAFE standard levels off GHG reductions in the 2020's. Post 2030 GHG emissions continue to decrease as more efficient and lower CI technologies are introduced into the fleet. As shown, the SAFE BAU GHG emissions are highest of all, and the SAFE Max BEV and Max E85 HEV cases yield higher emissions than the base BAU case until about 2043.

Figure 5-22 shows the difference in cumulative emissions relative to the base case BAU. The SAFE BAU results in 2 billion additional tonnes of GHG emissions than the BAU case while the SAFE Max BEV and Max E85 cases are higher than the BAU case by approximately 1 billion tonnes. In contrast, the two scenarios with the Obama era fuel economy standards yield a reduction of more than 5 billion tonnes of GHGs relative to the BAU.

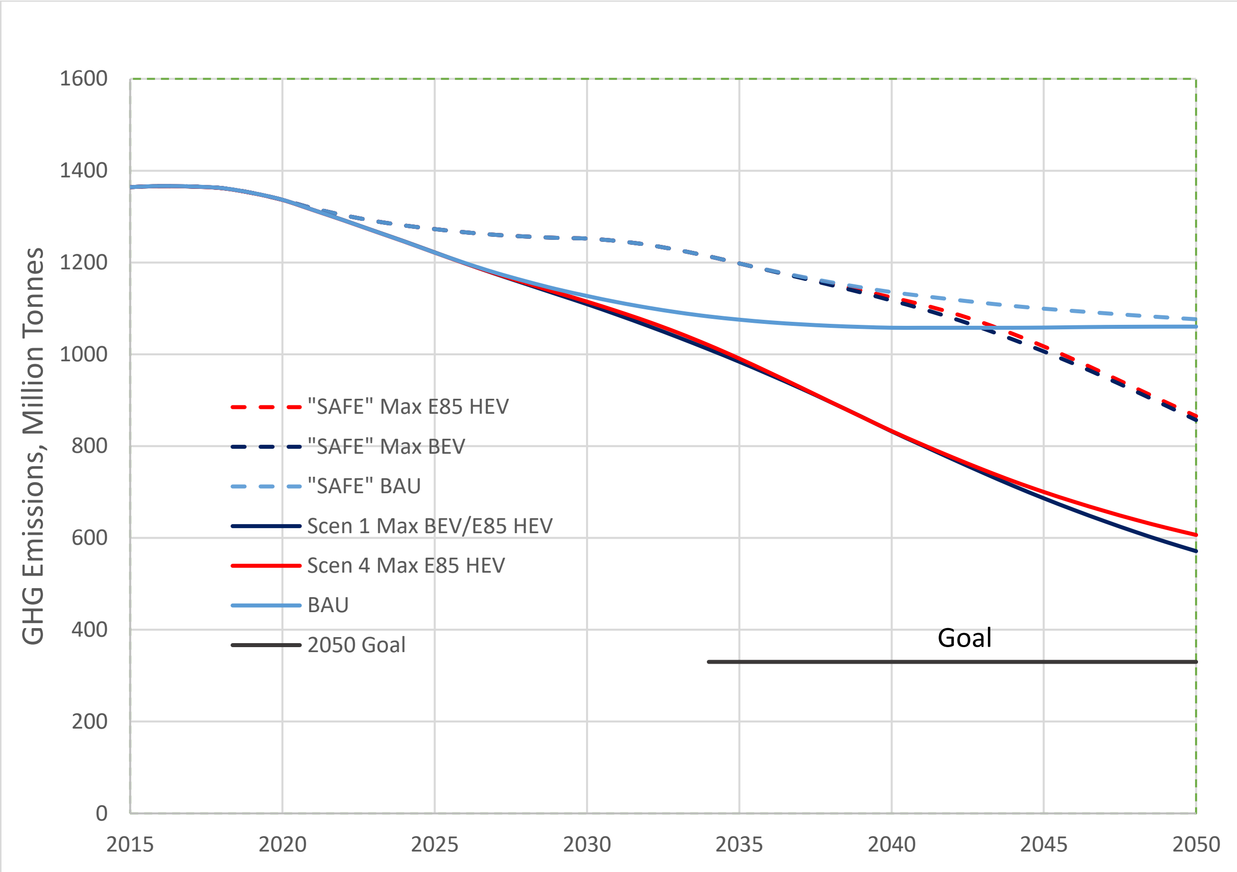


Figure 5-21. Cumulative (2015-2050) GHG emissions for SAFE cases compared to base cases.

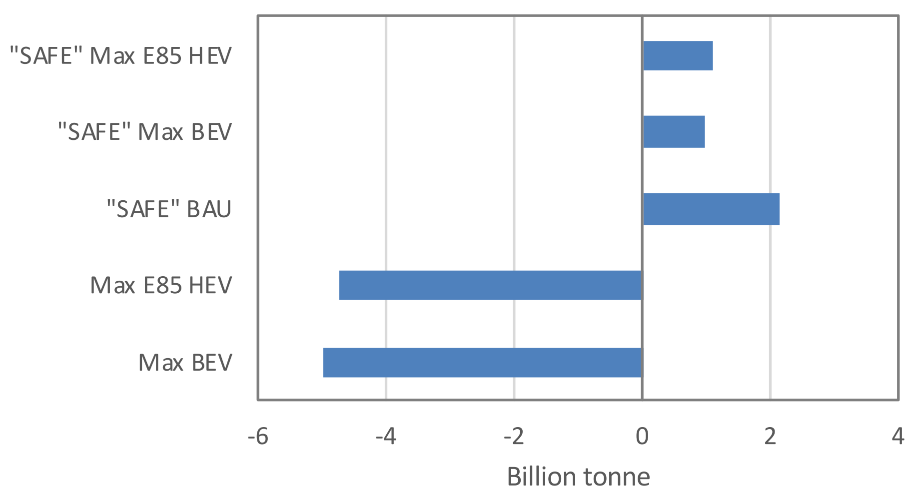


Figure 5-22. Change in cumulative (2015-2050) GHG emissions relative to base case BAU.

Total cumulative fuel consumption for the three SAFE cases and their corresponding base cases are illustrated in Figure 5-23. Again, the SAFE cases are all higher than the base cases, with the SAFE technology scenarios resulting in more total fuel consumption than the base case BAU. Figure 5-24 provides change in cumulative fuel consumption relative to the base case BAU. The SAFE BAU results in an additional 200 billion gallons of gasoline equivalent consumed over the analysis time frame compared to the BAU based on Obama era fuel economy standards. The SAFE technology scenarios increase cumulative fuel consumption by more than 100 billion gge while the base case technology scenarios decrease cumulative fuel consumption by as much as 420 billion gge. When considering changes in petroleum fuel consumption only (Figure 5-25), the base case scenarios decrease cumulative consumption by more than 600 billion gge while the SAFE technology scenarios increase petroleum consumption by 40 to 60 billion gge.

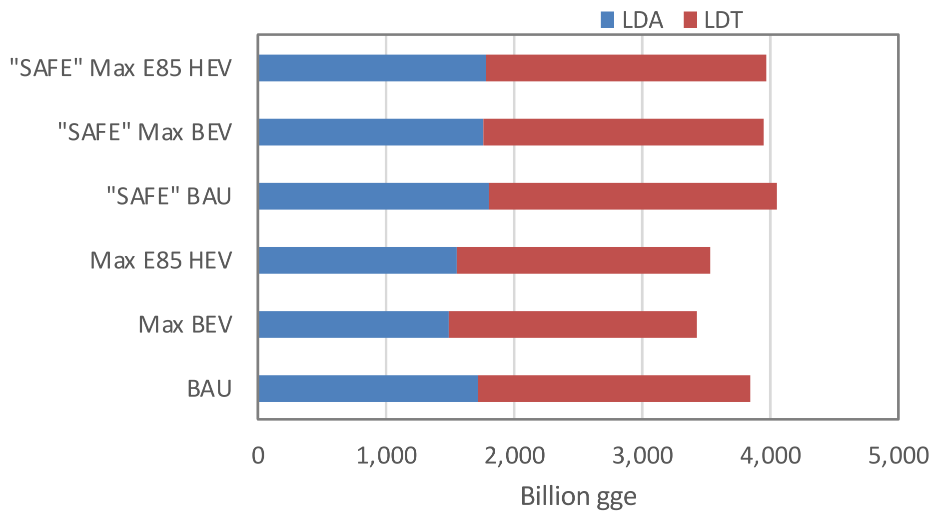


Figure 5-23. Cumulative (2015-2050) fuel consumption for SAFE cases compared to base cases.

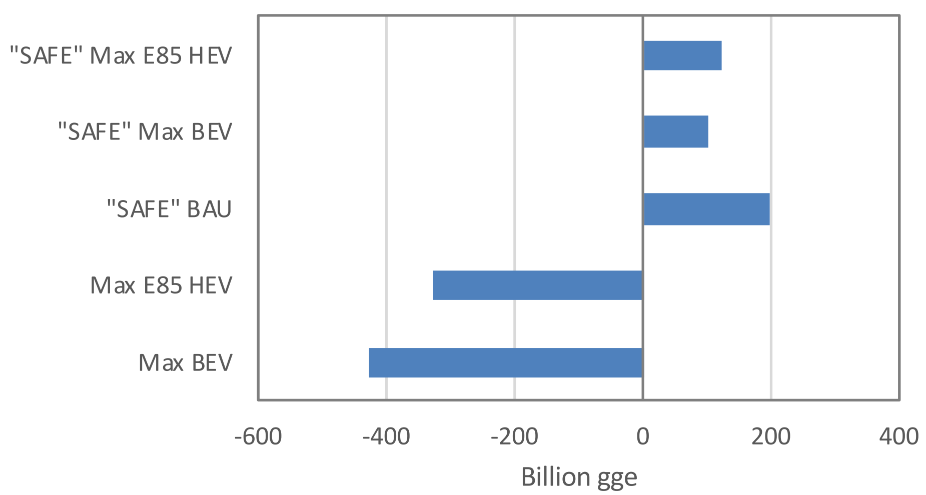


Figure 5-24. Change in cumulative (2015-2050) fuel consumption relative to base case BAU.

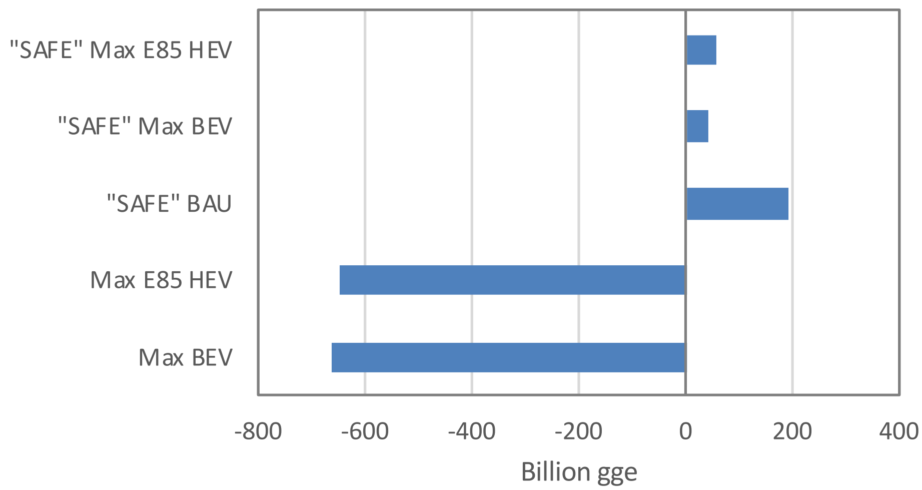


Figure 5-25. Change in cumulative (2015-2050) petroleum consumption relative to base case BAU

Cumulative consumer spending on vehicles, fuel and EVSE is illustrated in Figure 5-26. While the SAFE BAU and technology scenarios result in slightly less spending on vehicles, the increase in spending on fuel outweighs this saving, resulting in higher cumulative consumer spending than in the base cases which assumed Obama era fuel economy standards. Figure 5-27 provides a comparison of cumulative spending on vehicles, fuel and EVSE relative to the base case scenarios. As can be seen, the SAFE cases result in up to $500 billion higher spending than the base case BAU. In contrast, the base case technology scenarios provide between $400 and $800 billion in cumulative savings.

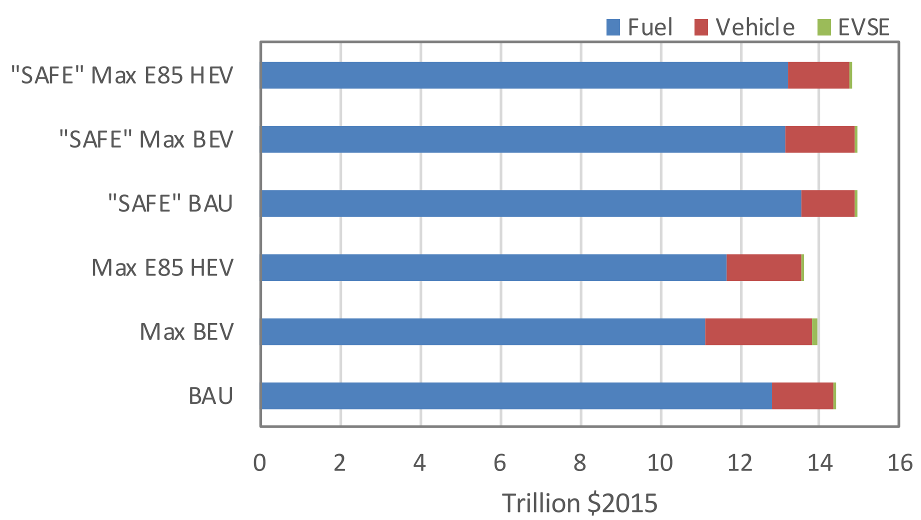


Figure 5-26. Cumulative consumer spending for SAFE and base case scenarios (2015-2050).

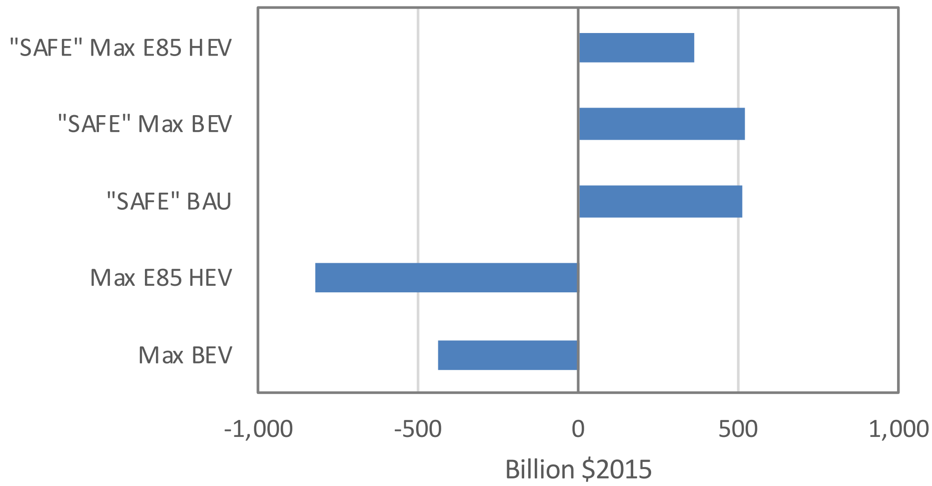


Figure 5-27. Cumulative consumer spending (2015-2050) relative to base case BAU.

The SAFE analyses are compared to the previous base cases in Table 5-6. As shown the 10-year delay in implementing more efficient technologies results in SAFE BAU cumulative GHG emissions increasing by 2 billion tonnes. The alternative scenarios are effective even more by the delay with the SAFE analyses increasing cumulative GHG emissions by 6 billion tonnes. Compared to the 80% reduction goal, these SAFE alternative scenarios reduce GHG emissions 48% by 2050 compared to the base case scenarios of 65%. Fuel use for the SAFE BAU increases by 200 billion gge relative to the BAU and by 527 billion gallons for the EV scenarios. The SAFE program also increases consumer spending by over $500 billion relative to the BAU.

Table 5-6. Summary of cumulative (2015-2050) results for base case and SAFE scenarios relative to base case BAU

Cumulative Results (2015-2050)	Units	Base Cases		SAFE Cases		
		Max BEV	Max E85 HEV	BAU	Max BEV	Max E85 HEV
GHG Emissions	Billion Tonne	-5.0	-4.7	2.1	1.0	1.1
Fuel Use	Billion gge	-426	-329	200	101	123
Petroleum Use	Billion gge	-662	-646	193	40	59
Costs						
Vehicle	$Billion	1094	322	-179	204	-45
Fuel	$Billion	-1671	-1142	691	286	407
EVSE	$Billion	156	0	-3	31	-3
Total	$Billion	-421	-820	509	521	359
Cost Effectiveness	$/tonne	-84	-174	238	532	329

5.9 Additional Illustrative Scenarios

To gain further insight on strategies to reduce GHG emissions and their costs, three additional scenarios/subcases were evaluated. This section describes these scenarios and their results. Recall that the maximum electrification scenarios capped market share at 70% for light autos and 45% for light trucks. For these scenarios, it was assumed that HEVs running on E85 would also be introduced to decrease conventional ICEV market share to 4% by 2050. It is of interest to determine the impact of operating these HEVs on E10 instead of E85, so the first subcase evaluated is Scenario 1 with conventional E10 HEVs substituted for the E85 HEVs. This results in a 2050 E10 HEV market share of 15% for LDA and 45% for LDT. The cumulative GHG reductions relative to BAU for Scenario 1 and each of its subcases are provided in Figure 5-28. Switching from E85 HEVs to E10 HEVs results in a 12% reduction in cumulative GHG reduction; this is half of the penalty associated with cancelling CPP standards.

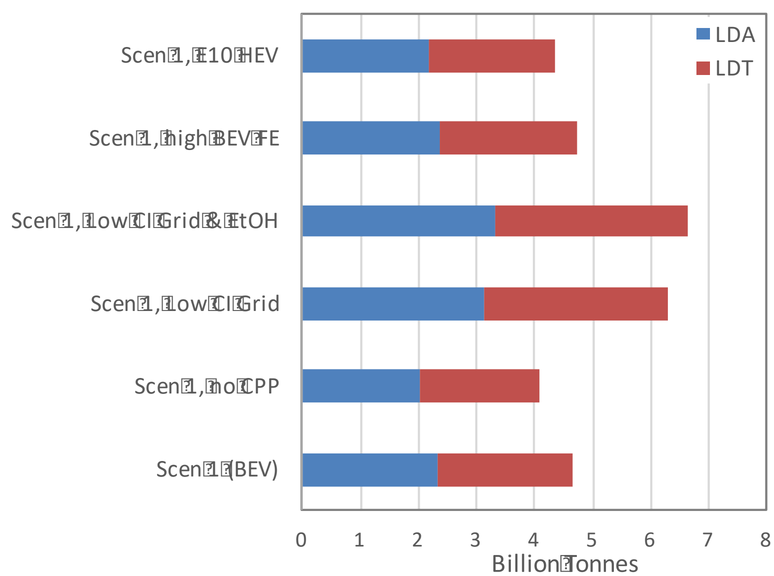


Figure 5-28. Scenario 1 cumulative (2015-2050) GHG reductions relative to BAU.

Annual ethanol consumption for Scenario 1 with E85 HEVs and the subcase in which E10 HEVs are substituted for E85 HEVs is illustrated in Figure 5-29. While Scenario 1 (BEVs with E85 HEVs) experiences nearly a doubling in ethanol consumption, the subcase with E10 HEVs cuts 2050 ethanol use by more than half relative to the base case.

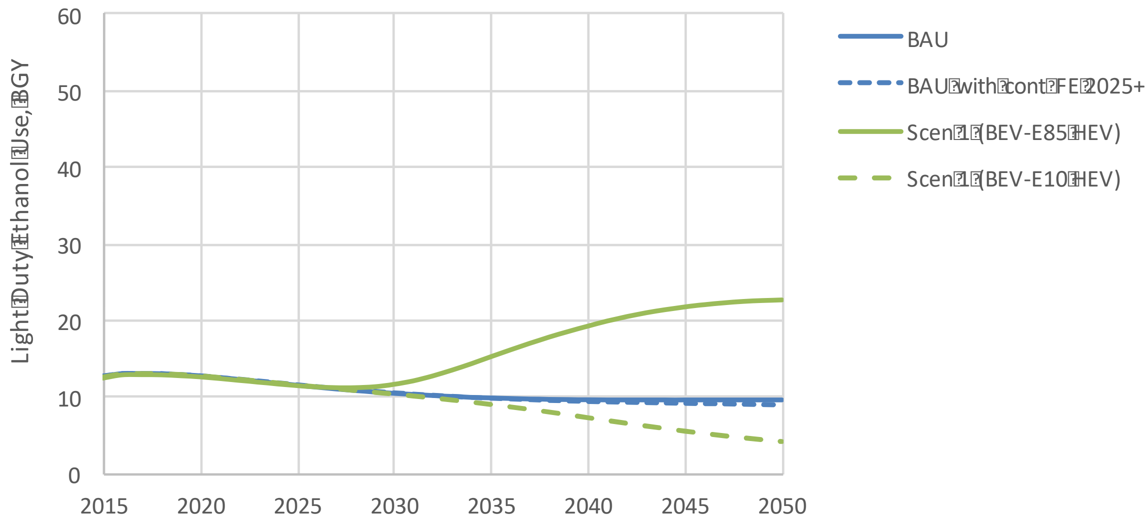


Figure 5-29. Annual ethanol consumption for Scenario 1 and the E10 HEV subcase.

Changes in vehicle and fuel spending for the E10 HEV subcase are shown in Table 5-7 for Scenario 1 and all its subcases. The E10 HEV subcase has more cumulative fuel savings and slightly lower vehicle spending because E85 fuel and E85 vehicles are more expensive than E10 and conventional HEVs. This more cumulative cost savings than the other BEV cases.

Table 5-7. Cumulative (2015-2050) U.S. light-duty costs relative to BAU for E10 Case

Billion $2015	Fuel Spending	Vehicle Spending	EVSE (Chargers)	Cumulative Cost
Scen 1 (BEV)	-1,671	1,094	156	-421
Scen 1, No CPP	-1,671	1,094	156	-421
Scen 1, Low CI Grid	-1,671	1,094	156	-421
Scen 1, Low CI Grid & EtOH	-1,478	1,094	156	-228
Scen 1, E10 HEVs instead of E85	-1,749	1,057	156	-535

The Scenario 1 E10 HEV subcase is added to the cumulative cost vs cumulative reduction plot in Figure 5-30. As indicated, this subcase provides less cumulative GHG reduction than the base case but is one of the best from a cost standpoint. If the E10 subcase was combined with a 70% non-fossil grid, we estimate cumulative GHG reduction at 5.7 billion tonnes (compared with 4.4 billion tonnes) at the same cumulative cost. While the base case and the E10 HEV subcase benefit greatly from a low CI grid, the base case offers the potential for additional reduction due to low CI ethanol which the E10 HEV subcase is not able to capture. If FFV HEVs were deployed instead of dedicated E10 or E85 HEVs, then Scenario 1 would have slightly increased vehicle costs, slightly lower fuel economy since the vehicles would not be optimized for E85 but would have the capability of taking advantage of low CI ethanol if it becomes available.

Figure 5-30. Cumulative cost and GHG reduction for Scenario 1 E10 HEV subcase.

The second add-on scenario considered was maximum deployment of E30 HEVs. This scenario assumes a rapid ramp of E30 HEVs to 90% market share by 2050 starting in 2025. Figure 5-31 provides the projected denatured ethanol consumption for this scenario. A slight increase over current levels is required, about half of the 2022 quantity stipulated in the RFS (36 BGY), and significantly less than the Max E85 HEV scenario consumption (the scenario with the highest projected ethanol consumption).

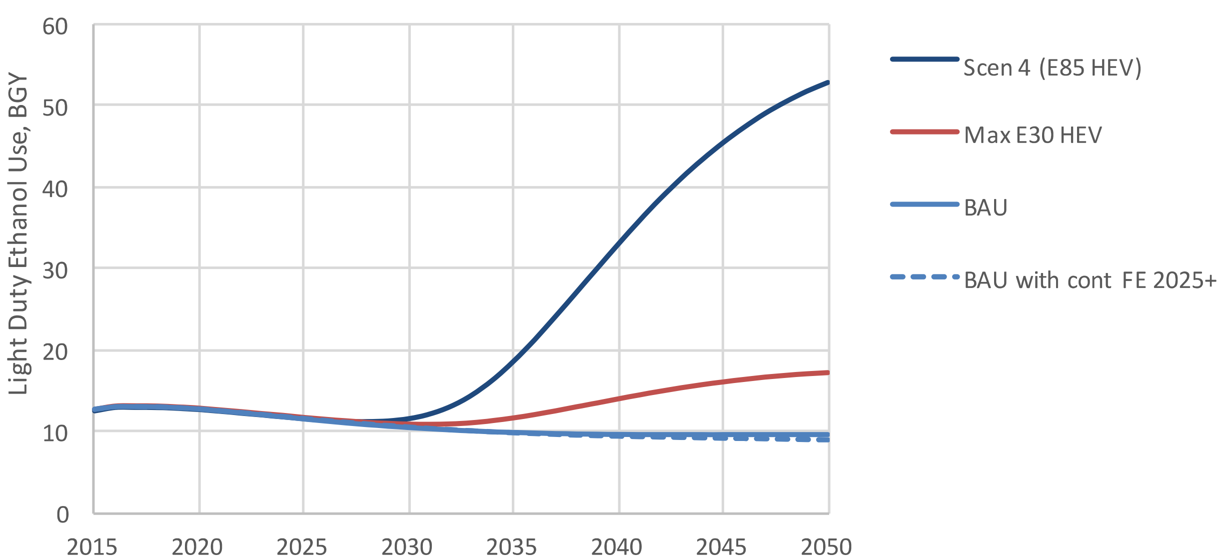


Figure 5-31. Denatured ethanol consumption for Max E30 HEV scenario.

Cumulative GHG reduction relative to BAU is provided in Figure 5-32 for the Max E30 and Max E85 scenarios. The low CI ethanol blend results are also shown; these scenarios provide a 3.8

billion tonne reduction with the base case ethanol CI and a 4.3 billion tonne reduction with the low CI ethanol mix. Of all the scenarios and their variations considered, the Max E30 scenario provides the lowest cumulative GHG reduction except for Scenario 2b (PHEV with light truck CNG).

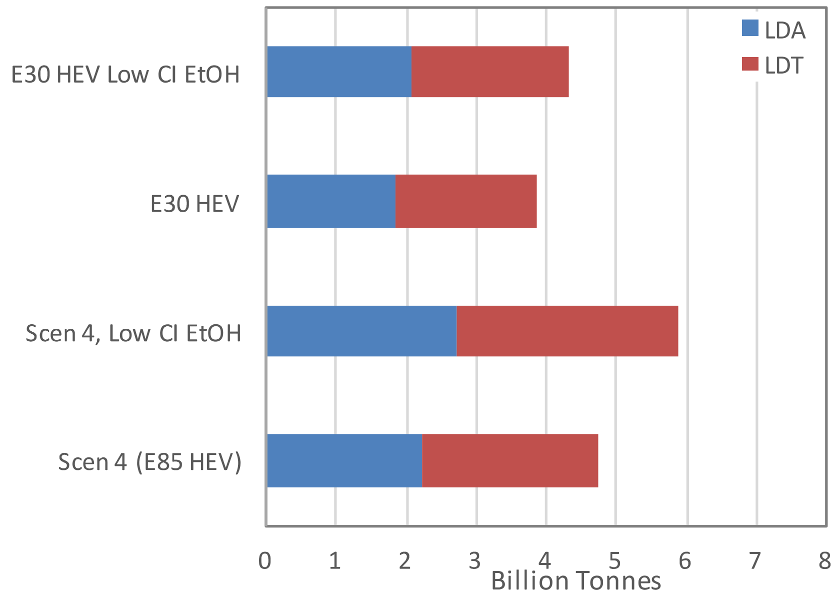


Figure 5-32. E30 HEV and E85 HEV cumulative (2015-2050) GHG reduction relative to BAU.

The cumulative change in spending on fuel, vehicles and EVSE relative to the BAU is provided in Table 5-8; Scenario 4 (Max E85 HEV) values are also provided for comparison. Since E30 is less expensive than E85, the fuel savings for the E30 case are greater than the E85 case. Dedicated E85 vehicle costs are slightly higher than E30 vehicles, so the cumulative vehicle costs for the E30 case are slightly lower than for the E85 HEV scenario.

Table 5-8. Cumulative (2015-2050) costs relative to BAU for Max E30 and E85 HEV Cases

Billion $2015	Fuel Spending	Vehicle Spending	EVSE (Chargers)	Cumulative Cost
Scen 4, Max E85 HEV	-1,142	322	0	-820
Scen 4, Low CI EtOH	-797	322	0	-475
Max E30 HEV	-1,282	306	0	-976
Max E30 HEV, Low CI EtOH	-1,137	306	0	-832

Figure 5-33 compares GHG reduction and cumulative cost of the Max E30 HEV cases to the other scenarios. These cases provide less cumulative GHG reduction (even with low CI ethanol) than most of the other cases with a modest increase in cumulative cost saving. As expected, the E85 HEV case realizes more GHG reduction benefit from switching to low CI ethanol than the E30 HEV case.

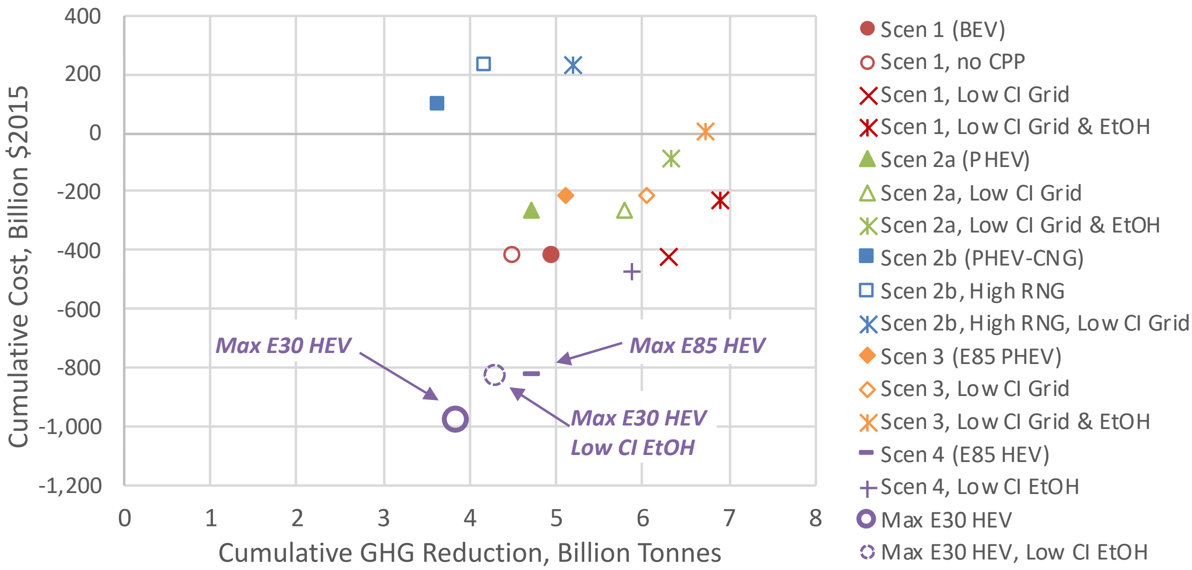


Figure 5-33. Cumulative cost and GHG reduction for Max E30 HEV case

Finally, the last add-on case quantifies the impact of transitioning reformulated gasoline from E10 to E15 in the near-term. Because cumulative GHG reductions are more important than the 2050 GHG emissions, rapidly transitioning to E15 can provide an early reduction while advanced vehicle technologies roll into the fleet. For this sub-case, we consider Scenario 3 (Max E85 PHEV) and assume that the reformulated gasoline increases denatured ethanol content from E10 to E15 by 2022. Figure 5-34 illustrates the annual projected ethanol use for each of the scenarios. Scenario 3 with E15 has a step increase in the near-term and then approaches the Scenario 3 value in the out years as the population of gasoline vehicles decreases.

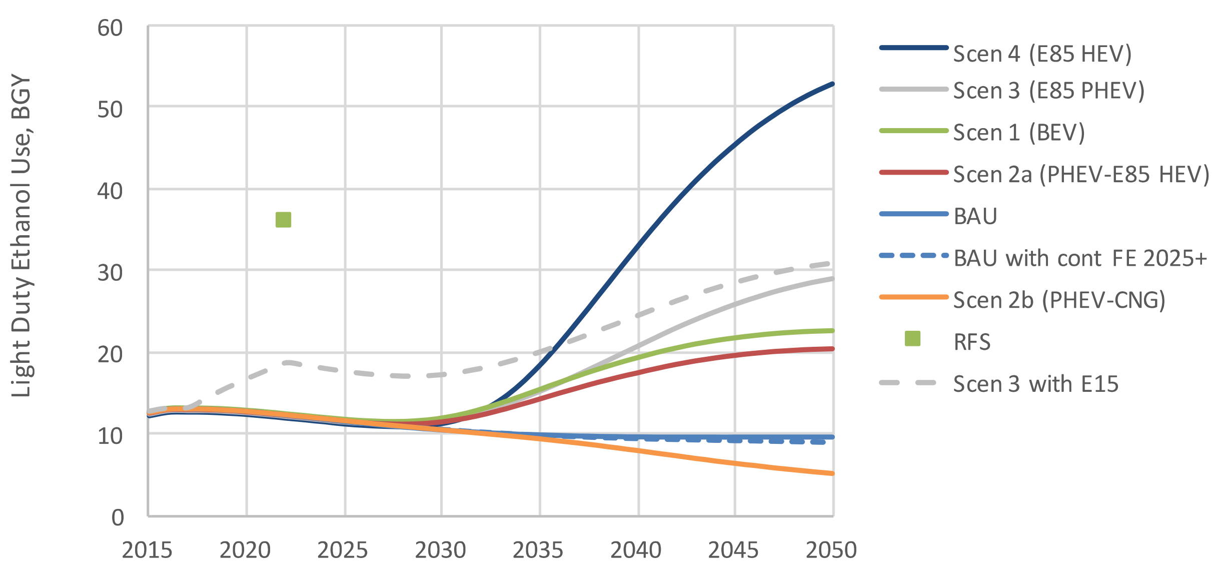


Figure 5-34. Denatured ethanol consumption for Scenario 3 with E15

Cumulative GHG reduction relative to the BAU case for all of the Scenario 3 E85 PHEV variations is provided in Figure 5-35. Switching from E10 to E15 yields a 5% increase in cumulative GHG emission reduction relative to BAU (270 million tonnes). Adding a low CI grid and low CI ethanol yields a cumulative reduction of 7.1 billion tonnes, the most of any scenario considered.

Cumulative costs relative to BAU for these Max E85 PHEV cases are summarized in Table 5-9. The base E15 case has the same fuel savings as the E10 case because we assume that RFG as E10 has the same price as RFG as E15. For the low CI cases, since the E15 version consumes more cellulosic ethanol than the E10 case, the cumulative fuel savings are lower.

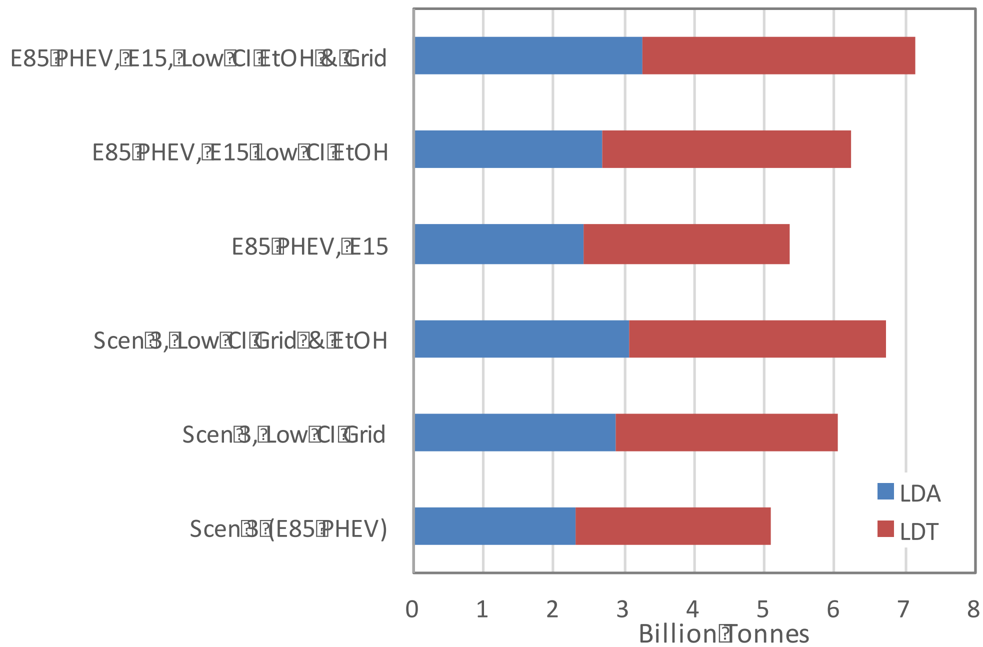


Figure 5-35. Cumulative (2015-2050) GHG reduction relative to BAU for Scenario 3 variations

Table 5-9. Cumulative (2015-2050) costs relative to BAU for Scenario 3 Max PHEV cases

Billion $2015	Fuel Spending	Vehicle Spending	EVSE (Chargers)	Cumulative Cost
Scen 3 (E85 PHEV)	-1,624	1,352	62	-211
Scen 3, Low CI Grid	-1,624	1,352	62	-211
Scen 3, Low CI Grid & EtOH	-1,406	1,352	62	8
Scen 3, E15	-1,624	1,352	62	-211
Scen 3, E15, Low CI EtOH	-1,364	1,352	62	49
Scen 3, E15, Low CI Grid & EtOH	-1,364	1,352	62	49

Finally, cumulative cost as a function of cumulative GHG reduction for these Scenario 3 subcases are illustrated in Figure 5-36. For the baseline fuel CI cases, the use of E15 provides 270 million additional tonnes of GHG reduction for no increase in cost. With the addition of a low CI grid and low CI ethanol, utilizing E15 instead of E10 provides an additional 420 million tonnes of GHG reduction for an additional $42 billion, or a cost per tonne of 99 $/tonne. The extra cost is due entirely to the assumed cost premium of cellulosic ethanol ($1/gal). It is likely that if 15 BGY of cellulosic ethanol were being produced as needed for the E15 low CI ethanol case, the price premium of cellulosic ethanol would decrease significantly.

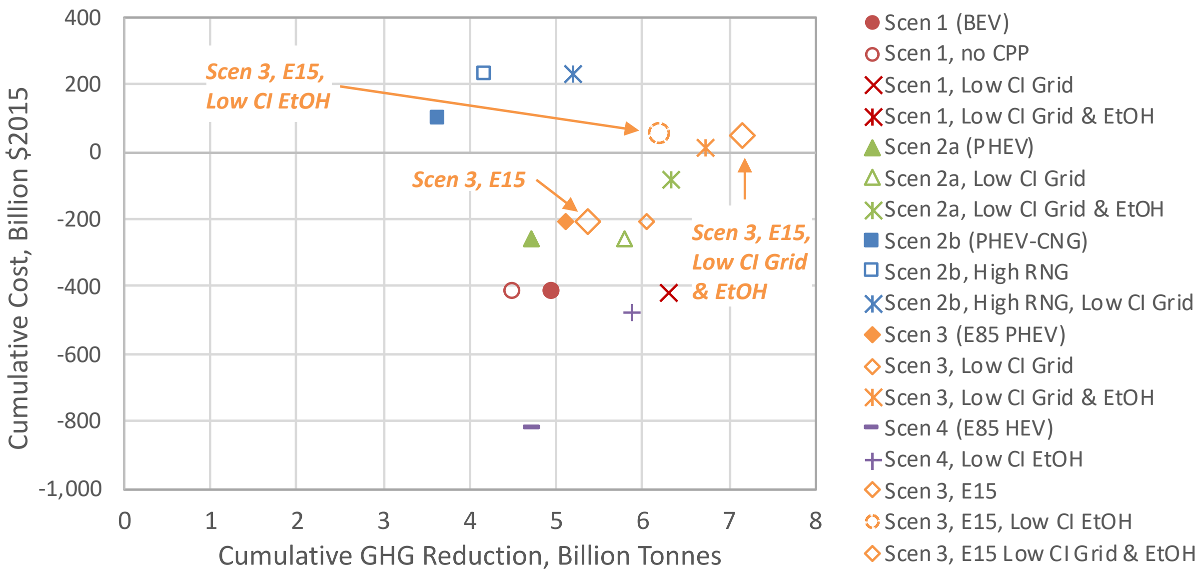


Figure 5-36. Cumulative cost and GHG reduction for Scenario 3 variations.

6. Scenario Analysis – CA Fleet

For the California light-duty fleet, the objective of this analysis is to determine if an 80% GHG emission reduction from 1990 levels is possible, and if so, what is needed in terms of vehicle technology sales and fuel sales. To answer these questions, CA scenarios were developed to maximize the market penetration of each promising low GHG emission technology and fuel type identified in Section 4.2. The midterm report by EPA, ARB and NHSTA indicated that the 2025 standards could largely be achieved with advanced gasoline ICE vehicles. Consequently, by 2025 most new car sales are still projected to be gasoline ICE vehicles. To continue GHG reductions, vehicle platform electrification or low-CI fuels or their combination will be required. Therefore, alternative scenarios were developed to maximize favorable technologies with various levels of electrification and low-CI fuels to reduce GHGs by 80% by 2050. The following sections describe the scenarios and analysis results.

6.1 Scenario Definition

In parallel to the U.S. analysis, four main scenarios emphasized a different key vehicle technology (BEV, PHEV, E85 PHEV, E85 HEV). While total vehicle sales in all scenarios remain the same as in the BAU case, each increases the market share of one of the four technologies at the expense of gasoline ICE vehicles. Maintaining total fleet population and VMT assumptions, the altered technology market shares change fuel consumption quantity and type, lowering overall GHG emissions.

Table 6-1 shows the 2050 market share for the vehicle technologies in each scenario. Note that the California BAU has significantly higher market share of alternative fuel vehicles than the U.S. average analysis. Only 67% of 2050 light-duty autos is forecast to be gasoline ICE compared to 85% for the U.S. overall. This is due to California's Zero Emission Vehicle Mandate, which requires sales of BEVs, PHEVs, and FCVs.

The following guidelines were used to adjust new vehicle market shares for the scenarios:

- To fairly compare scenarios, gasoline ICE market shares in each scenario were decreased to 2% for LDA and LDT.
- All other technology shares were maintained at BAU levels unless otherwise noted.
- Because BEV market share is limited by homes with EVSE access, it is assumed that maximum BEV market share is 70%, and maximum PHEV market share is 80% for LDA.
- Because electrification is not currently compatible with towing capability, maximum LDT market share for BEVs and PHEVs is 45%. To maximize LDT alternative vehicles, PHEVs and BEVs were supplemented with E85 HEVs or NGVs.
- E85 HEVs are assumed to have a faster ramp up to market penetration than plug-in options because incremental price is lower, range is not an issue, and charging capability is not required.

Table 6-1. New vehicle market share assumptions for California analysis scenarios

Scenario	2050 LDA Market Share	2050 LDT Market Share
BAU	67% Gasoline ICE 1% Diesel 14% Gasoline HEV 5% BEV 10% PHEV 3% FCV	85% Gasoline ICE 1% Diesel 1% Gasoline HEV 2% BEV 6% PHEV 3% FCV 1% CNG
1. Max BEV	70% BEV 2% Gasoline ICE All others BAU	43% BEV 43% E85 HEV 2% Gasoline ICE All others BAU
2a. Max PHEV/E85 HEV	75% PHEV 2% Gasoline ICE All others BAU	45% PHEV 45% E85 HEV 2% Gasoline ICE All others BAU
2b. Max PHEV/CNG	Same as 2a	45% PHEV 46% CNG 2% Gasoline ICE All others BAU
3. Max E85 PHEV	65% E85 PHEV 2% Gasoline ICE All others BAU	43% E85 PHEV 43% E85 HEV 2% Gasoline ICE All others BAU
4. Max E85 HEV	65% E85 HEV 2% Gasoline ICE All others BAU	83% E85 HEV 2% Gasoline ICE All others BAU

Figure 6-1 and Figure 6-2 illustrate the assumed California LDA and LDT new vehicle market shares for the BEV-dominant Scenario 1. These new vehicle market shares are similar the U.S. assumptions for BEV sales. For light duty autos BEVs ramp up quickly to 70% by 2050 with gasoline ICE sales declining just as quickly. BEV LDT sales are constrained to 45% and HEV sales also make up 45% of sales in 2050. HEV sales happen more quickly than BEV sales, but BEV sales—due to the ZEV mandate—start earlier than HEV sales. Earlier BEV sales will result in lower GHG emissions. Refer to Appendix E for corresponding figures for California Scenarios 2 through 4.

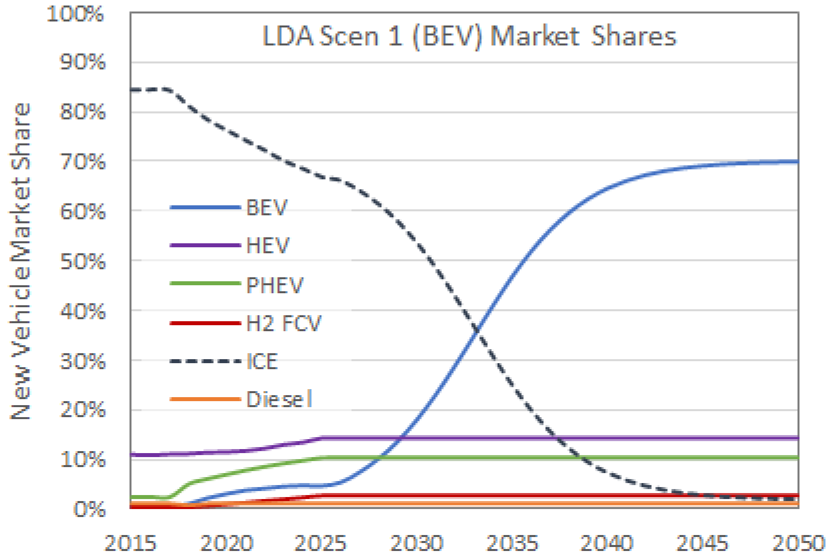


Figure 6-1. California LDA assumed new vehicle market shares for Scenario 1

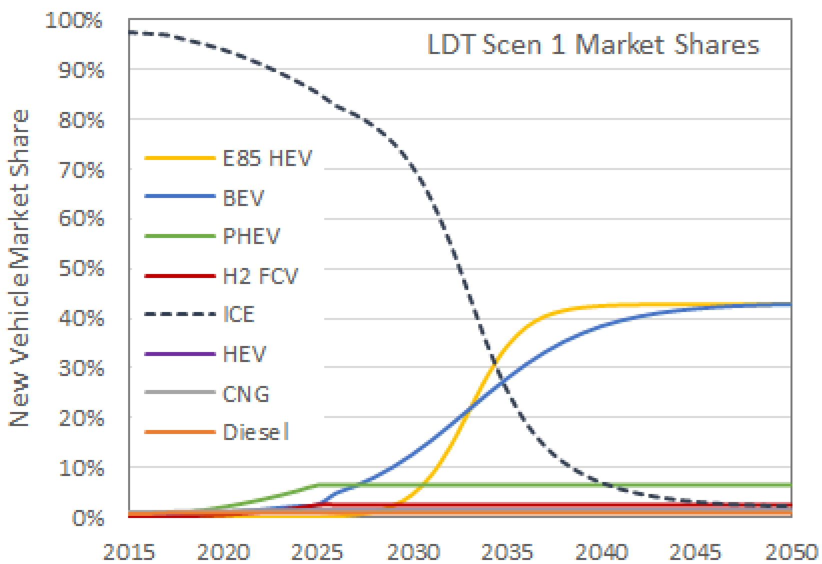


Figure 6-2. California LDT assumed new vehicle market shares for Scenario 1

The scenarios were also evaluated with the following fuel mix assumptions:

- Scenarios 1-3 (plug-in technologies) were evaluated with two sets of CI values: California BAU grid mix and 70% non-fossil grid mix.
- All scenarios were evaluated with the base case ethanol mix and a low-CI ethanol mix (Please see Section 2.6).
- Scenario 2b was evaluated with base case RNG (Section 2.6). Because the base case has a high fraction of RNG, a high RNG case was not evaluated.

It is doubtful that the GHG reduction scenarios will occur without regulatory drivers such as continued CAFE pressure and/or a federal ZEV Mandate. It is therefore assumed for the GHG reduction scenarios that auto manufacturers will continue improving fuel economy of existing vehicles for 2026-2050. Refer to Section 2.5 for the assumed improvement in vehicle fuel economy for the GHG reduction scenarios. Two BAU cases were included: BAU with no improvement in fuel economy for 2025-2050 and BAU with continuing/incremental fuel economy improvement post 2025.

6.2 Fuel Volumes

A key metric of this analysis is fleet fuel consumption. Projected California light-duty fuel use is provided in Figure 6-3. Due to improving fuel economy, BAU fuel use declines steadily through 2030 as more efficient vehicles replace older models. Consumption holds steady from 2030 to 2040 and then begins to rise through 2050 due to increasing vehicle populations. For the BAU case with continuing fuel economy improvement (but no change in vehicle technology market shares), fuel use remains constant from 2040 through 2050 as higher fuel economy offsets the increase in vehicle population.

The maximum electrification cases (1, 2a, 3) all result in a 68 to 71% reduction in fuel use between 2015 and 2050. Scenario 2b is slightly lower at 67%. Since electric vehicles are about 3 times more fuel efficient than conventional vehicles, the non-electrification scenario (Scenario 4 Max HEV) reduces fuel use by only 62%. Figure 6-4 shows predicted decreases in petroleum consumption. The BAU case reduces petroleum use 43-48%, while scenario reductions range from 82-87%.

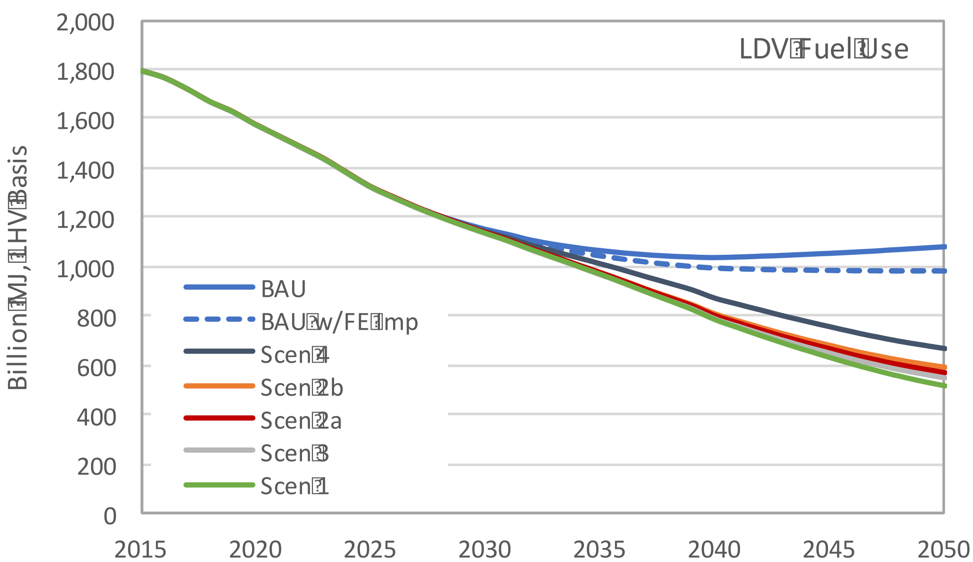


Figure 6-3. Projected California total light-duty fuel use

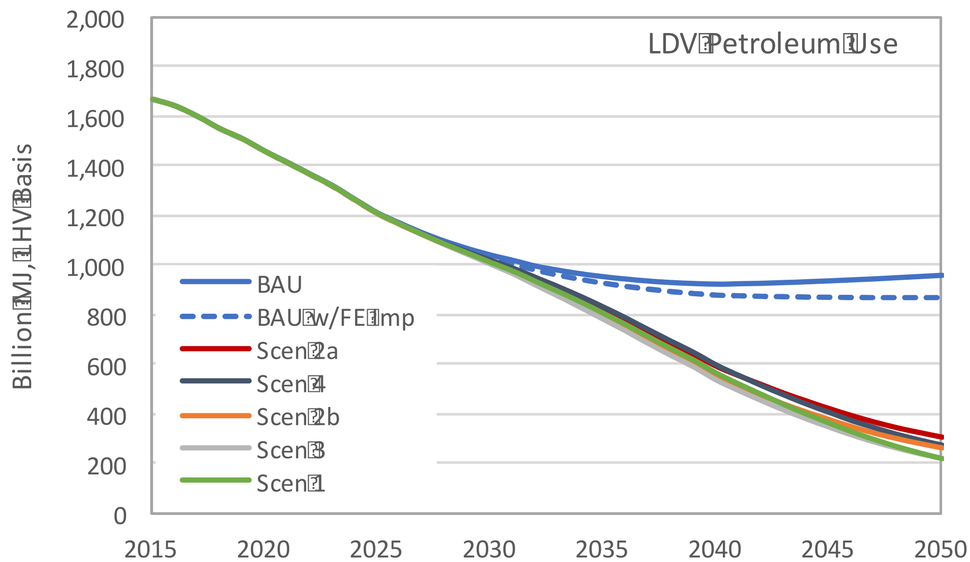


Figure 6-4. Projected California light-duty petroleum consumption

Figure 6-5 shows the projected total ethanol consumption for each of the scenarios. For BAU, ethanol use is expected to decrease 43% from 2015 levels. With continued fuel economy improvements 2025-2050, ethanol use is projected to decrease by 48% to under 800 MGY in 2050. Scenario 2b decreases ethanol consumption by 84% (230 MGY in 2050) due to the high market share of light truck CNG vehicles. Scenarios 1 and 2a reduce ethanol use by 18% and 10%; Scenario 1 has more light duty auto E85 HEVs than scenario 2a due to maximum penetration of BEVs at 70% compared to maximum PHEV penetration of 80%. Scenario 3, focusing on E85 PHEVs is predicted to increase ethanol use by 50% compared to current consumption. Finally, the non-electrification Scenario 4 requires a tripling of ethanol use to nearly 4.5 BGY in California.

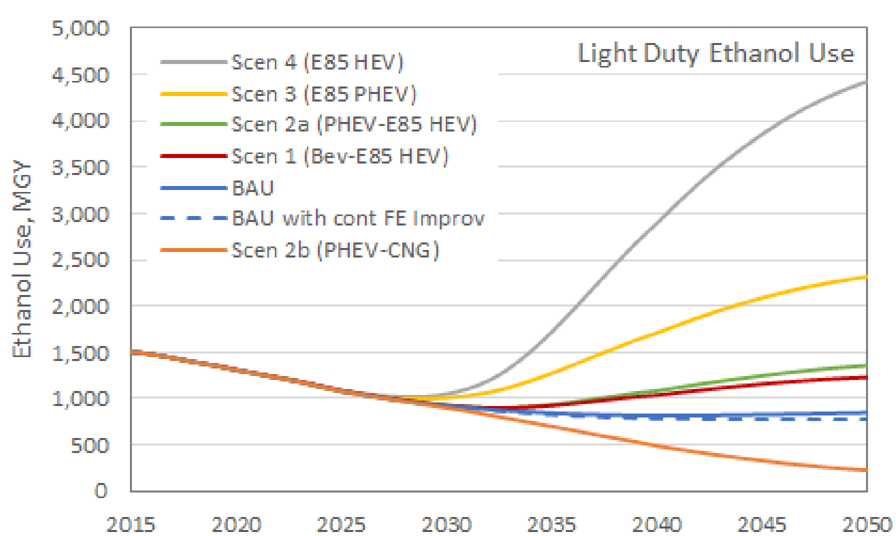


Figure 6-5. Projected California light-duty ethanol volumes for BAU and scenarios

Finally, projected cellulosic ethanol consumption is shown in Figure 6-6. The BAU case assumes that 400 MGY will be used, consistent with ARB's most recent LCFS compliance projection.[70] Low-CI Scenario 4 requires the most cellulosic ethanol, up to 3 BGY by 2050. According to DOE's Billion Ton Update described above, this consumption level is well within domestic production potential.

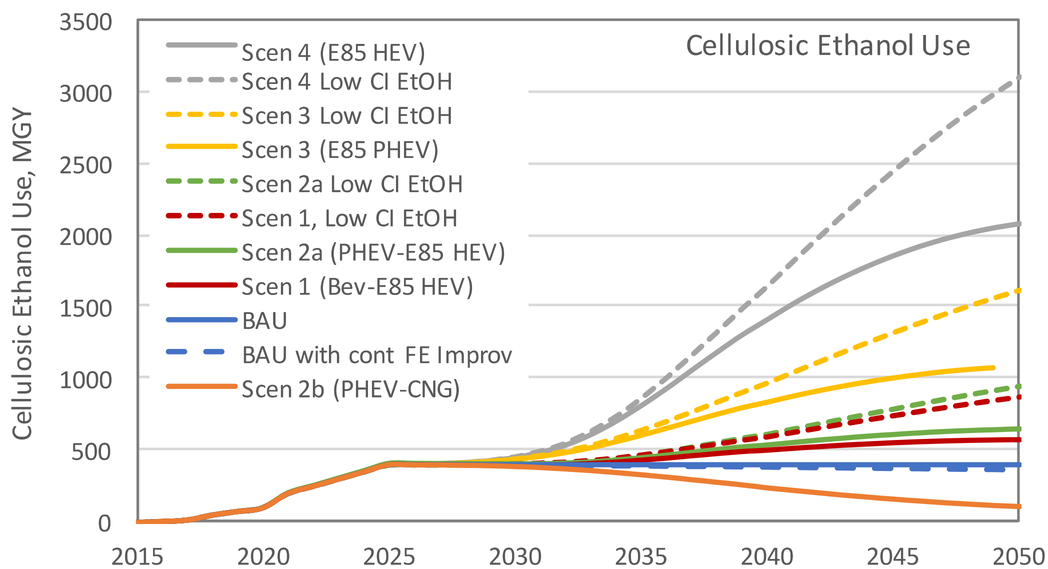


Figure 6-6. Projected California light-duty cellulosic ethanol volumes

Figure 6-7 illustrates the anticipated RNG volumes for BAU and the scenarios. Scenario 2b's large penetration CNG light trucks requires over 1 billion gallons per year of diesel equivalent (BGYde) of RNG for the light fleet by 2050. ARB has projected 450 million gallons per year of diesel equivalent (MGYde) of RNG for the entire on-road fleet mostly composed of medium- and heavy-duty trucks by 2025. Adding ARB estimate to that of Scenario 2b would result in total on-road demand (light, medium and heavy-duty) of over 1.5 BGYde by 2050. This is well under what is thought to be the U.S. commercial potential (refer to footnote 42) by the American Gas Association, but more than the potential recently estimated by UC Davis researchers (footnote 43).

[70] LCFS Update to Illustrative Compliance Scenarios, April 2015

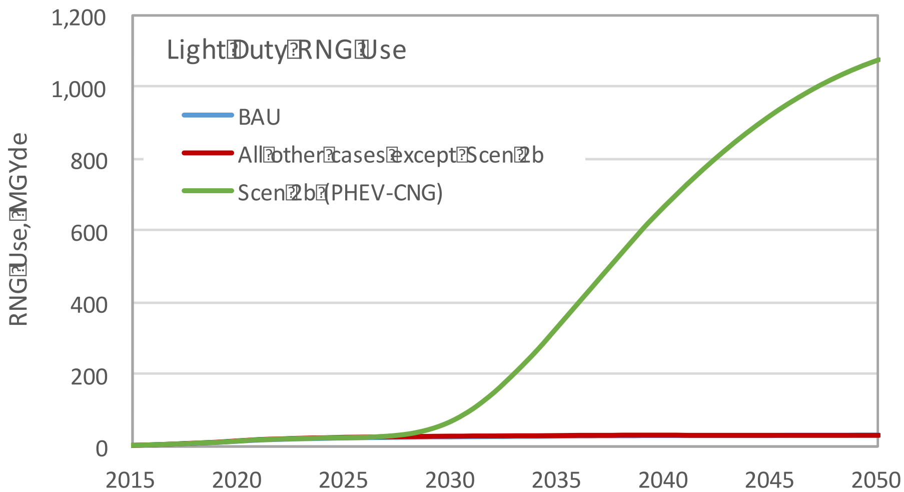


Figure 6-7. Projected California light-duty RNG volumes

6.3 GHG Emission Reduction

Figure 6-8 and Figure 6-9 provide LDA and LDT GHG emissions over time for the BAU case and each of the scenarios. As discussed in Section 4.2, multiple individual vehicle and fuel combinations achieve the 2050 goal of 80% GHG reduction. However, as shown in Figure 6-10, even with aggressive market share assumptions for the cleanest technologies, the California light-duty fleet does not achieve the 2050 goal in any of the scenarios. More time is needed for older vehicles to be replaced with more efficient, less carbon intensive options, the cleaner options must be adopted sooner than assumed, or other measures such as increased gasoline and HEV fuel economy, higher penetration of ZEV technologies or larger VMT reductions must be achieved. All the base CI scenarios (solid lines) yield similar GHG emission levels in 2050. The low-CI (dashed lines) BEV and E85 PHEV options provide slightly more reduction than the low-CI PHEV and E85 HEV options. This is clearly shown in

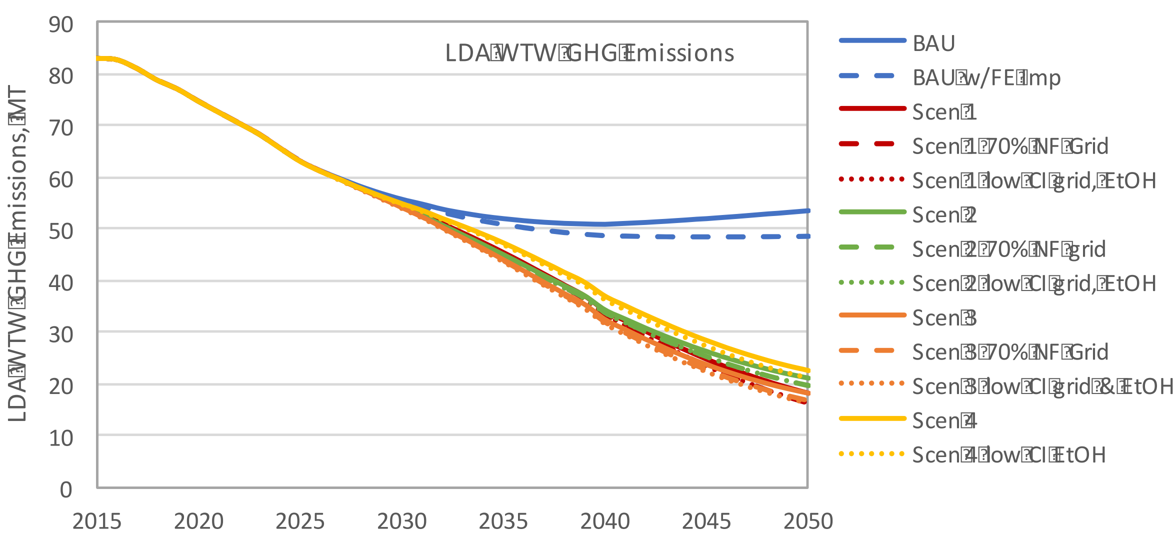


Figure 6-8. Projected California LDA GHG emissions

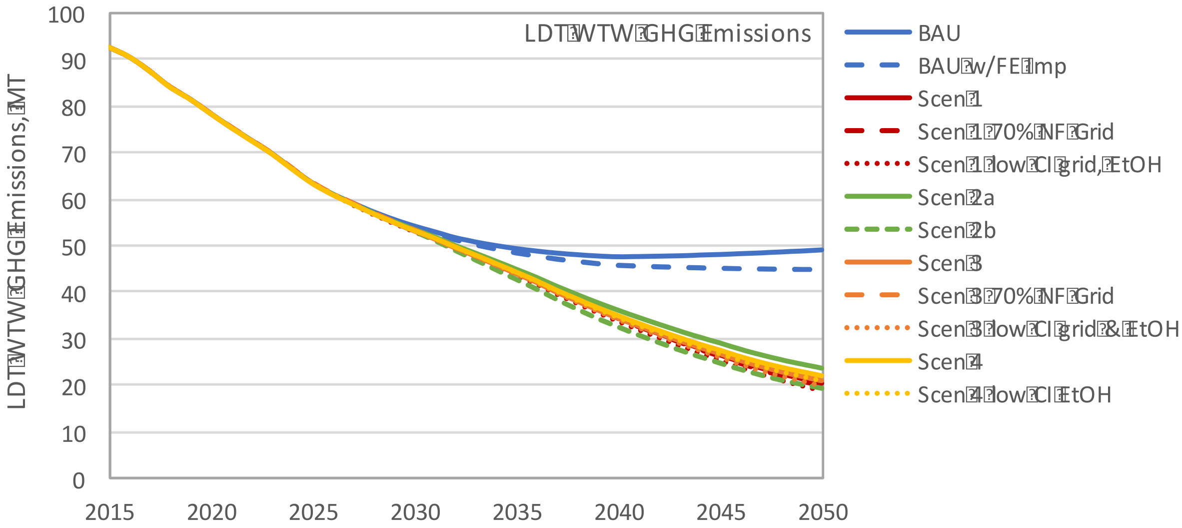


Figure 6-9. Projected California LDT GHG emissions

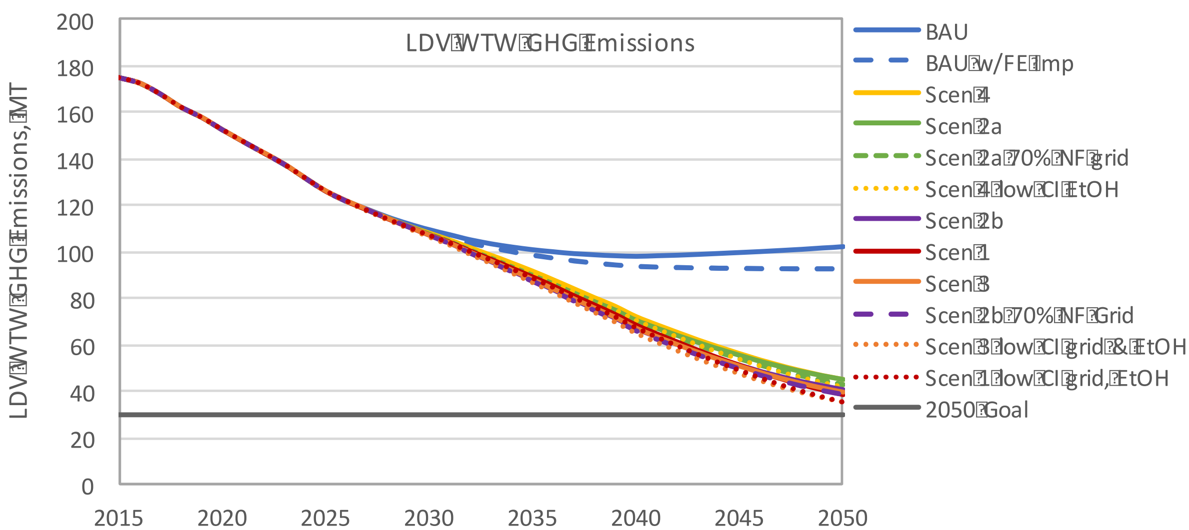


Figure 6-10. Projected California total light-duty GHG emissions Table 6-2 which provides the 2050 emission levels for each scenario.

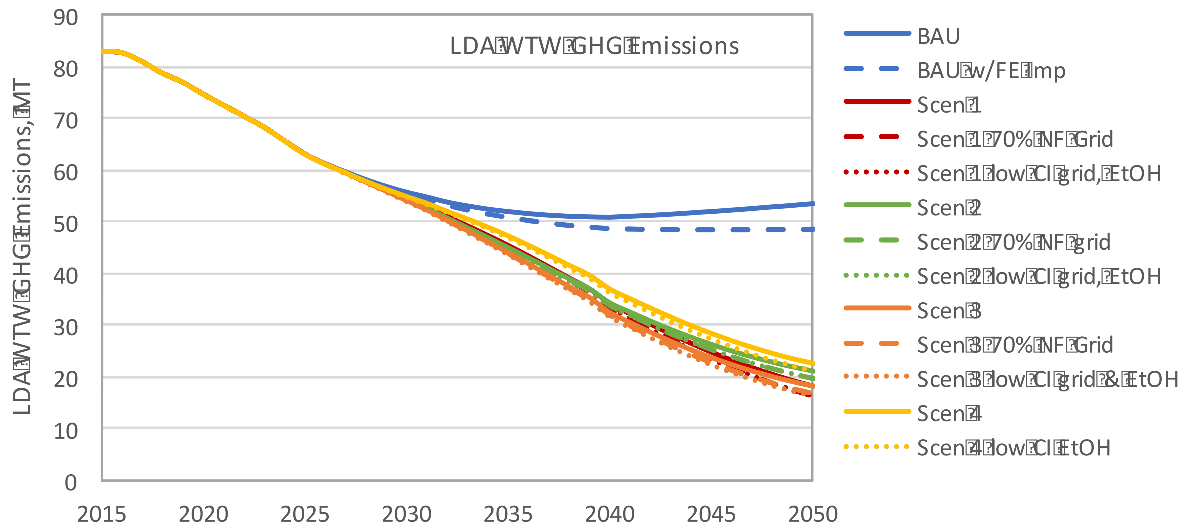


Figure 6-8. Projected California LDA GHG emissions

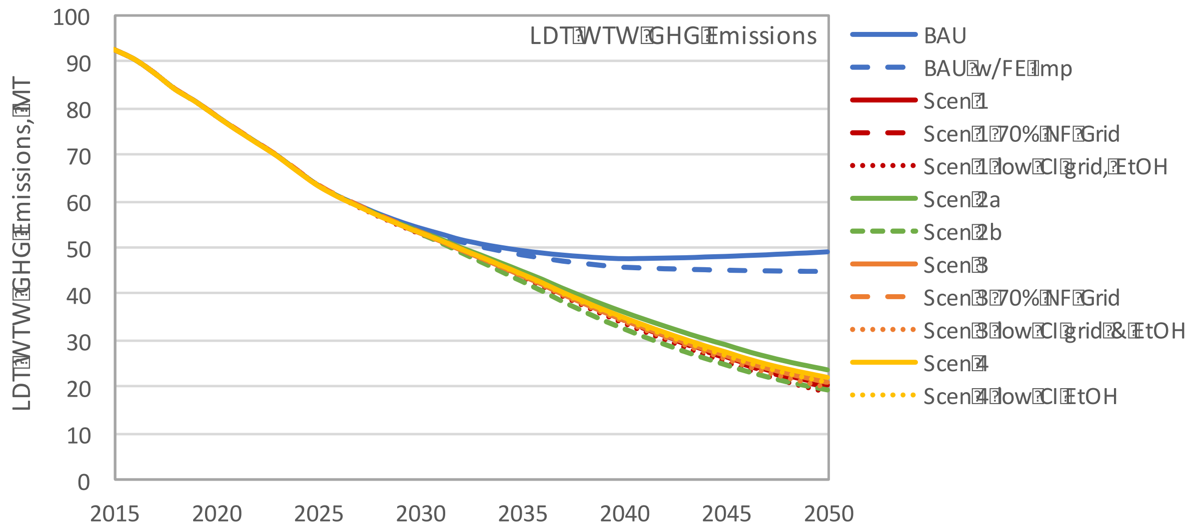


Figure 6-9. Projected California LDT GHG emissions

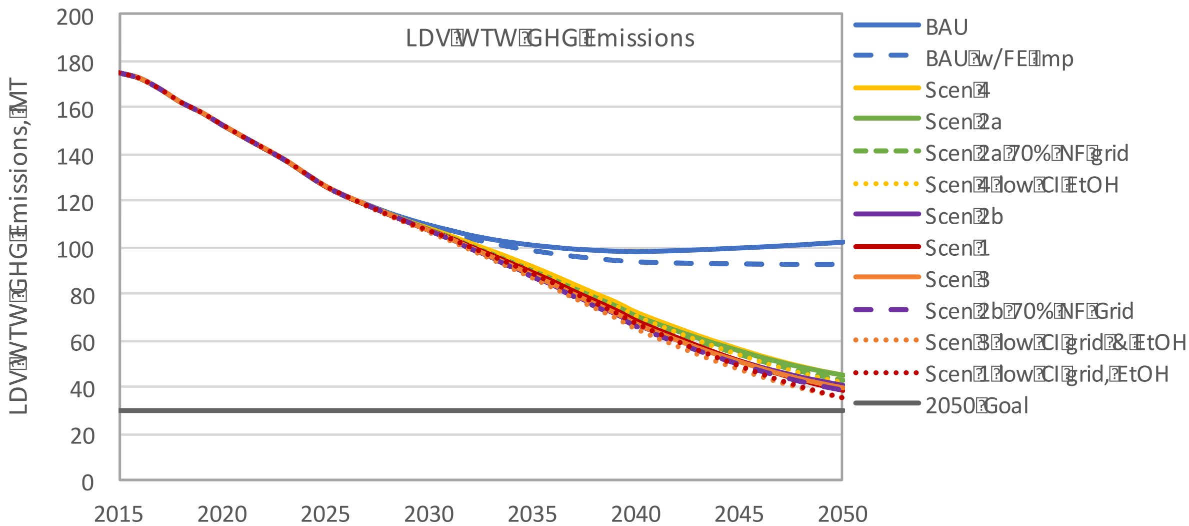


Figure 6-10. Projected California total light-duty GHG emissions

Table 6-2. Summary of California 2050 GHG Emissions by Scenario

2050 GHG Emissions	Light Duty Auto		Light Duty Truck		Light Duty Fleet	
	M tonne	Reduction	M tonne	Reduction	M tonne	Reduction
BAU	53.5		49.0		102.5	
BAU with Cont FE Improv	48.5	9%	44.7	9%	93.2	9%
Scen 1 BEV+E85 HEV	18.3	66%	20.4	58%	38.8	62%
Scen 1 BEV+E85 HEV, low CI grid	16.4	69%	19.7	60%	36.1	65%
Scen 1 BEV+E85 HEV, low CI grid & EtOH	16.4	69%	18.9	61%	35.3	66%
Scen 2a E10 PHEV+E85 HEV	21.3	60%	23.7	52%	45.0	56%
Scen 2a E10 PHEV+E85 HEV, low CI grid	19.7	63%	23.3	53%	43.0	58%
Scen 2a E10 PHEV+E85 HEV, low CI grid & EtOH	19.7	63%	22.5	54%	42.1	59%
Scen 3 E85 PHEV + E85 HEV	18.2	66%	21.2	57%	39.4	62%
Scen 3 E85 PHEV+E85 HEV, low CI grid	16.7	69%	20.7	58%	37.4	64%
Scen 3 E85 PHEV+E85 HEV, low CI grid & EtOH	16.3	70%	19.7	60%	35.9	65%
Scen 4 E85 HEV	22.8	57%	22.3	54%	45.1	56%
Scen 4 E85 HEV, low CI EtOH	21.3	60%	21.0	57%	42.3	59%

There is little difference between the BAU and low CI fuel cases due to California's LCFS and renewable grid. Figure 6-11 indicates that because of the LCFS, the BAU CI (42 g CO_2 e/MJ) and the low CI fuel case (34 g CO_2 e/MJ) yields only a 19% benefit in 2050. Similarly, Figure 6-12 shows that the electricity CI for the 70% non-fossil grid case is only 22% lower than the BAU electricity CI.

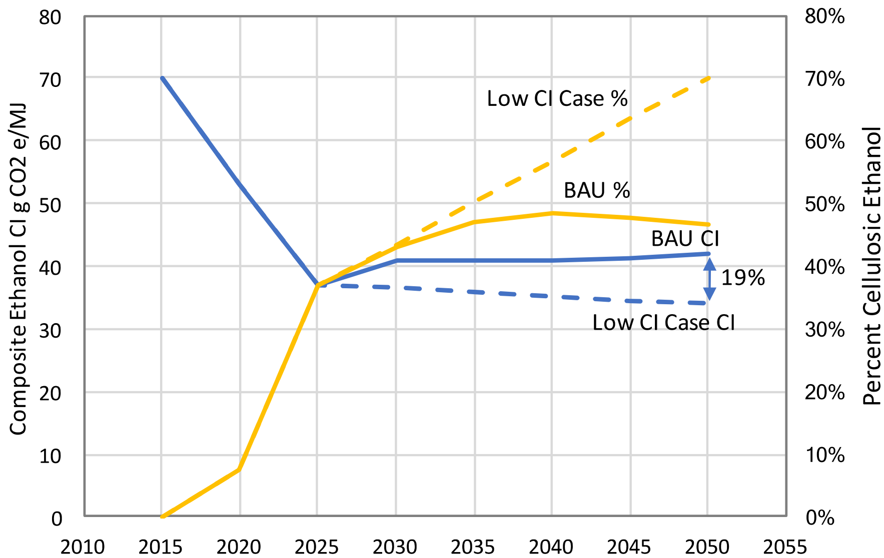


Figure 6-11. California ethanol composite carbon intensity for BAU and low CI scenario

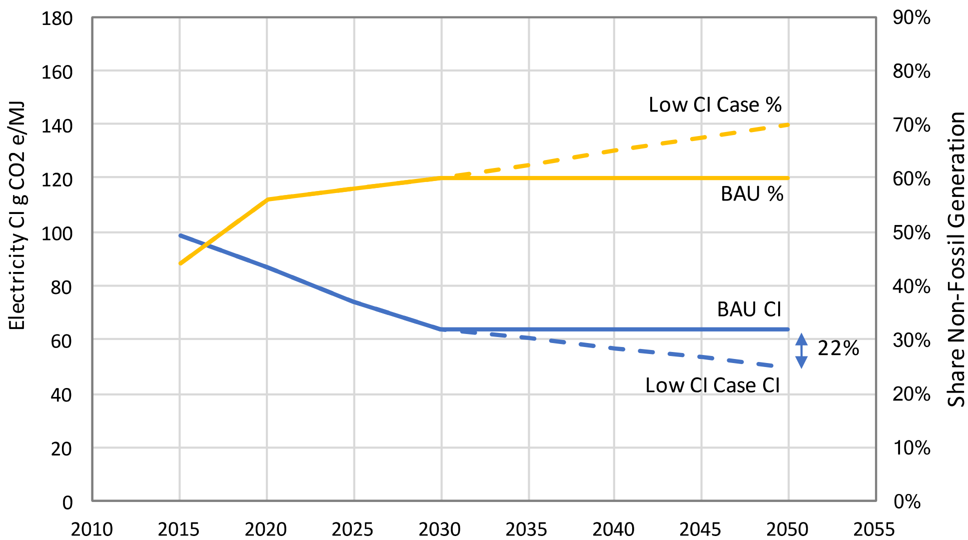


Figure 6-12. California electricity carbon intensity for BAU and low CI scenario

Because GHG emissions accumulate in the atmosphere, cumulative emissions are an important measure to compare the potential climate impact of each scenario. Figure 6-13 shows the cumulative GHG reductions (2015-2050) for each scenario for California. Scenarios 1, 2b and 3 offer similar reductions. The emissions for Scenario 2a with E85 HEVs are higher than Scenario 2b with CNG operating on high levels of RNG. Scenario 4 with low CI ethanol provides similar GHG reductions to Scenario 2a with base case fuel CI values.

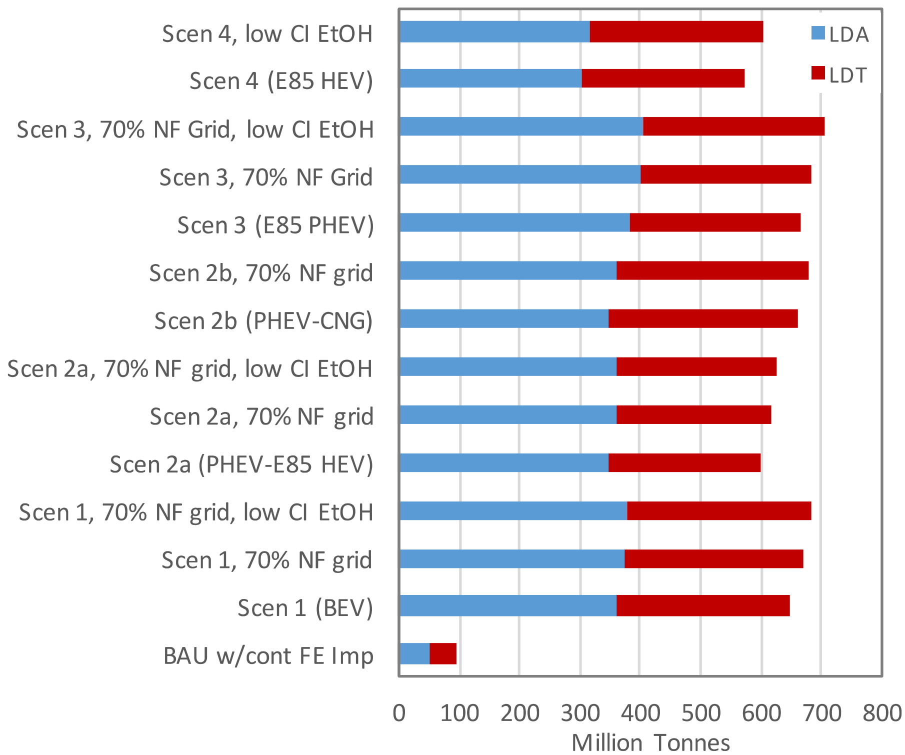


Figure 6-13. Cumulative California GHG reductions relative to BAU (2015-2050)

6.4 Change in Fuel Costs

Change in fuel spending is shown in Figure 6-14 and Table 6-3. Like the U.S. at large, all scenarios reduce fuel costs relative to BAU in California. Also, like the U.S., electrification options provide more fuel cost savings than the E85 HEV option. The BEV scenario with 20% higher electricity costs (1.2 factor) and 20% lower electricity costs (0.8 factor) are also shown. A 20% change in electricity price has a 10% impact on cumulative fuel costs. Scenarios with more ethanol use (particularly cellulosic ethanol) and RNG have higher RIN costs (in this analysis, the proxy for higher production costs). The U.S. federal tax credits for cellulosic ethanol, biodiesel and renewable diesel are assumed to expire in 2025 and therefore have no impact on results.

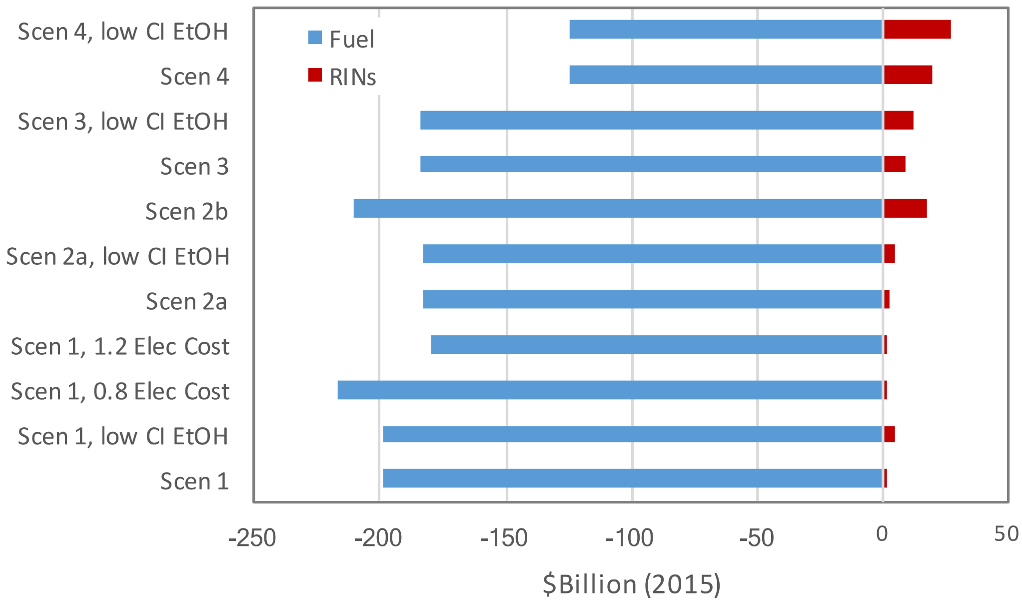


Figure 6-14. Change in California cumulative fuel spending relative to BAU (2015-2050)

Table 6-3. Summary of California cumulative (2015-2050) fuel costs relative to BAU

Billion $2015	Change in Fuel Spending	Change in RIN Costs	Net Change in Fuel Costs
Scen 1 (BEV)	-199	2	-197
Scen 1, low-CI EtOH	-199	4	-194
Scen 1, 0.8 Electricity Cost	-217	2	-215
Scen 1, 1.2 Electricity Cost	-180	2	-178
Scen 2a (PHEV-E85 HEV)	-183	2	-181
Scen 2a, low-CI EtOH	-183	5	-178
Scen 2b (PHEV-CNG)	-211	18	-193
Scen 3 (E85 PHEV)	-184	8	-175
Scen 3, low-CI EtOH	-184	12	-171
Scen 4 (E85 HEV)	-125	20	-105
Scen 4, low-CI EtOH	-125	27	-98

6.5 Change in Vehicle and EVSE Spending

The cumulative increase in vehicle spending relative to BAU is provided in Figure 6-15. The non-electrification Scenario 4 has the lowest incremental vehicle costs. Scenario 2b is the most expensive options due to higher natural gas light-duty truck costs. The BEV scenario vehicle costs are four times the E85 HEV scenario with PHEV and E85 PHEV scenarios progressively costlier. Plug-in vehicle costs do not include any income tax credit since this credit is expected to largely phase out by 2018[71].

The change in cumulative spending on residential EV charging equipment relative to the BAU case is shown in Figure 6-16. Scenario 1 incurs nearly three times the EVSE costs of Scenarios 2 and 3 while Scenario 4 is the same as BAU. However, EVSE costs are low (roughly 10% of incremental vehicle cost) relative to other costs.

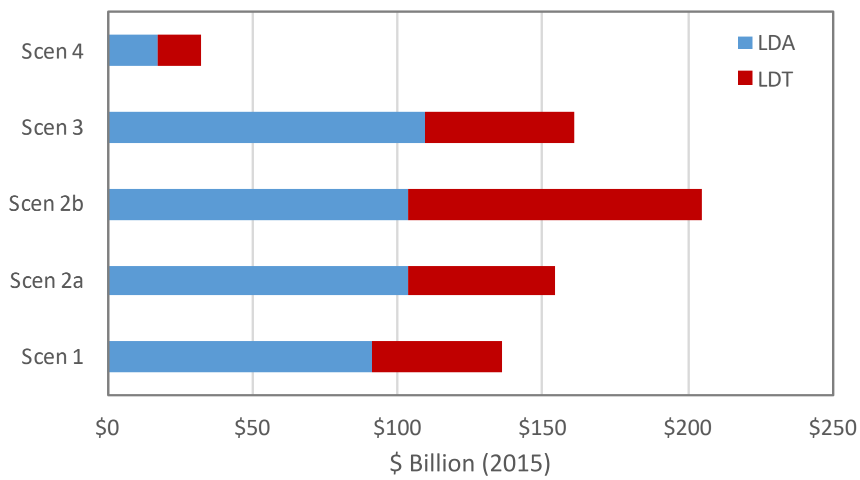


Figure 6-15. Change in California cumulative vehicle spending relative to BAU (2015-2050)

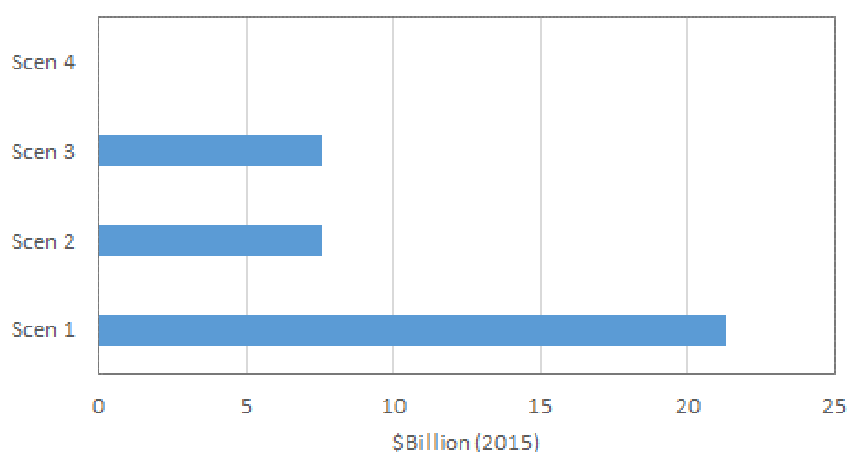


Figure 6-16. Change in California EVSE spending relative to BAU (2015-2050)

[71] The EV income tax credit allows purchasers to deduct up to $7500 from their income tax up until the manufacturer that produced the EV sells 200,000 plug in vehicles at which point the credit begins to phase out.

6.6 Cost Effectiveness

To compare the scenarios, overall cumulative cost (non-discounted) is summarized in Figure 6-17 and Table 6-4. The substantial (non-discounted) fuel cost savings relative to the BAU case are offset, and in the CNG case outweighed, by higher incremental vehicle costs. EVSE costs are more than an order of magnitude lower than fuel and vehicle savings and costs. Scenario 4 (E85 HEV) vehicle costs are approximately 2-3 times lower than the other scenarios because HEVs are less expensive than the electrification technologies that are the focus of Scenarios 1-3. However, fuel savings are less than half that of the other scenarios because the HEVs lack the higher efficiency and lower electricity costs of the BEVs and PHEVs. All scenarios except Scenario 2b provide net cumulative savings for California.

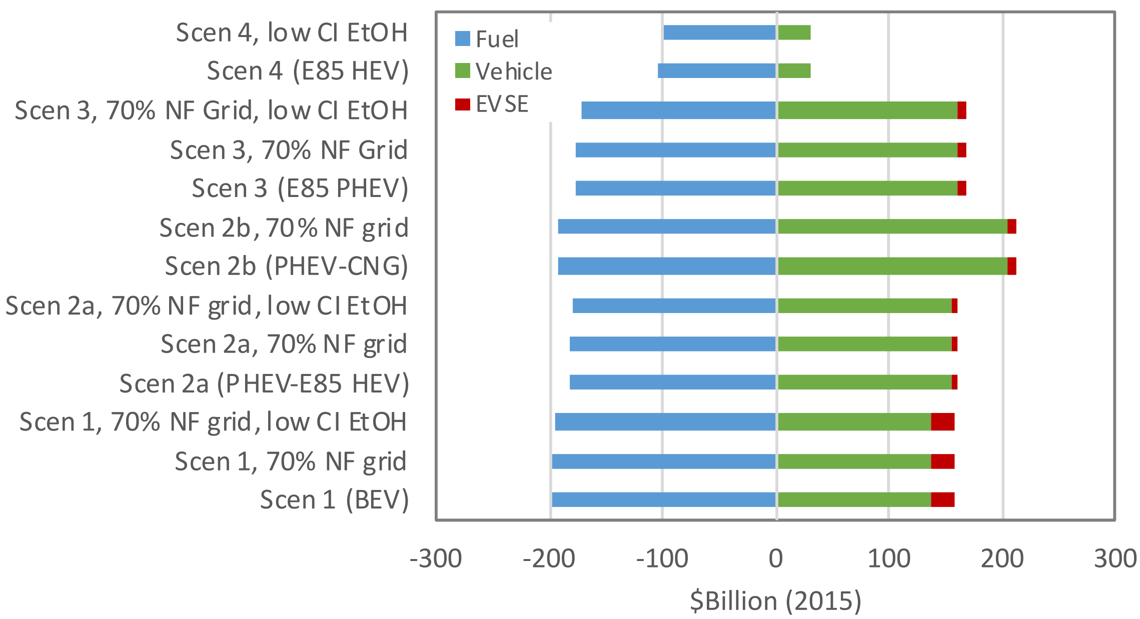


Figure 6-17. Change in California cumulative costs relative to BAU (2015-2050)

Table 6-4. Summary of California cumulative (2015-2050) total costs relative to BAU

Billion $2015	Fuel Spending	Vehicle Spending	EVSE (Charger)	Cumulative Cost
Scen 1 (BEV)	-196.6	136	21	-39
Scen 1, 70% NF grid, low-CI EtOH	-194.3	136	21	-37
Scen 2a (PHEV-E85 HEV)	-181.0	154	8	-19
Scen 2a, 70% NF grid, low-CI EtOH	-178.5	154	8	-17
Scen 2b (PHEV-CNG)	-192.8	205	8	20
Scen 3 (E85 PHEV)	-175.5	161	8	-7
Scen 3, 70% NF Grid, low-CI EtOH	-171.4	161	8	-3
Scen 4 (E85 HEV)	-105.1	32	0	-73
Scen 4, low-CI EtOH	-97.7	32	0	-66

Cost effectiveness, defined as cumulative costs relative to BAU divided by cumulative GHG reductions relative to BAU, is presented in Figure 6-18 and Table 6-5. Cost effectiveness ranges from a savings of $128 per tonne for Scenario 4 to a cost of $20 per tonne for Scenario 2b. Scenario 4 (E85 HEV) has ~ double the savings per tonne of Scenario 1 (BEV), the next most cost-effective scenario. Scenario 2b (PHEV+CNG) is the only scenario with positive cost effectiveness due to higher vehicle costs than the other scenarios.

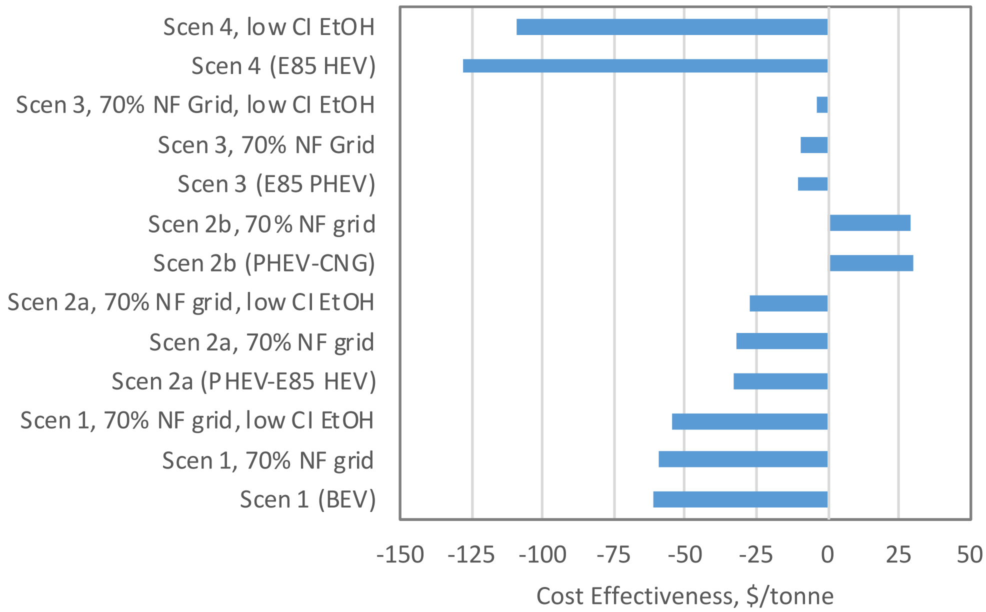


Figure 6-18. California cost effectiveness (cumulative cost / cumulative reduction)

Table 6-5. Summary of California analysis cost effectiveness

	Base Scenarios		Low-CI Options	
	Cost Effectiveness ($/tonne)	Cumulative Reduction (Million tonnes)	Cost Effectiveness ($/tonne)	Cumulative Reduction (Million tonnes)
Scen 1 (BEV/E85 HEV)	-61	648	-54	682
Scen 2a (PHEV/E85 HEV)	-33	597	--27	626
Scen 2b (PHEV/CNG)	30	661	29	679
Scen 3 (E85 PHEV/E85 HEV)	-10	667	-4	703
Scen 4 (E85 HEV)	-128	572	-109	603

Cumulative cost is plotted as a function of GHG reduction in Figure 6-19. Scenario 4 (E85 HEV, in yellow symbols on chart) with conventional ethanol is an interesting case since it provides modest GHG reduction at a significant cost savings relative to BAU. Vehicle cost is much lower than other scenarios because of smaller capacity batteries. It does, however, require substantial ethanol volumes (Figure 6-5). Scenario 4 requires 4.5 BGY of ethanol, approximately 3 times current consumption. Moreover, it requires over 2 BGY of cellulosic ethanol. While this scenario has minimal vehicle technology risk, it carries ethanol supply risk. The low-CI Scenario 4 provides more GHG reduction but requires even more cellulosic ethanol.

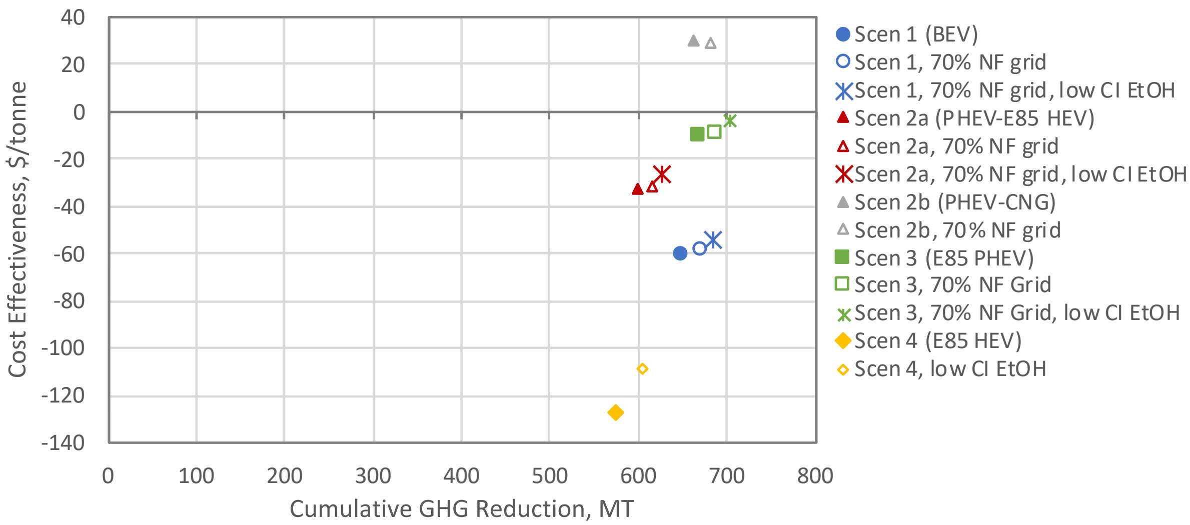


Figure 6-19. California cost effectiveness vs cumulative reduction

Scenario 1 (BEV) shown with blue symbols (●)provides large reductions in GHG emissions at approximately half of the savings of Scenario 4. Scenario 2a and its variations (▲)provide about half of the cumulative cost savings of the BEV scenario. It is interesting to note that in contrast to the U.S. analysis, the addition of low-CI grid and more low-CI ethanol does not dramatically reduce cumulative GHG emissions. The base case California grid is 60% non-fossil in 2050 and the base case ethanol is assumed to have 40% advanced ethanol. Scenario 2a provides similar GHG reduction to Scenario 4 with low-CI ethanol, with markedly lower cellulosic ethanol volumes (600 MGY vs 3.1 BGY).

Scenario 3 (E85 PHEV, in green symbols) in Figure 6-19 shows more reduction than Scenario 2a at a higher cost (though still provides a cost savings). The difference in cost is due to higher prices for E85 relative to gasoline on an energy basis (Figure 2-26) and slightly higher vehicle cost. Scenario 3 carries the risk of needing significant amounts of ethanol (2.3 BGY total ethanol, 1 BGY cellulosic).

Scenario 2b (PHEV-CNG, ▲) provides similar reduction to Scenario 2a (PHEV-E85 HEV), but at a higher cost. Scenario 2b, with elevated CNG vehicle market share has higher vehicle costs which are somewhat offset by lower fuel prices (CNG being less expensive than gasoline). Again, the low-CI grid and ethanol options do not have a large impact on either GHG reduction or price because the BAU CI values in California are like the low-CI versions.

Table 6-6 ranks the results by assigning a score in each of four categories: GHG reduction, cost, vehicle technology risk, and fuel risk. Each category is given equal weight to calculate a single score for each scenario. The simplistic scoring system assigns -1 points to red grades, +1 points to green grades and 0 points to blue grades and then normalizes total score on a scale of 1 to 5. Scenario 3 (E85 PHEV) receives the top score of 5 due a combination of high GHG reduction, low cost and low fuel supply risk. The Scenario 3 options with low CI fuels have lower scores due to higher fuel supply risk without significant improvement in GHG reduction.

The BEV and PHEV scenarios with conventional ethanol receive scores of 4; the addition of low CI fuels increases fuel supply risk without significant improvement in GHG reduction, so the scores drop. As stated previously, Scenario 4 is attractive despite modest GHG reductions because of its low cost. However, Scenario 4's score is reduced because of the risk associated with the large increase in ethanol demand. As noted in Section 5, estimates indicate that there is enough cellulosic feedstock to produce enough ethanol for Scenario 4, it is just a question of technical and commercial feasibility. Natural gas could also be used as an ethanol feedstock, but the CI value is not favorable.

Table 6-6. California scenario ranking based on four criteria

	GHG Reduction	Cost	Vehicle Technology Risk	Fuel Supply Risk	Overall Score
Scen 1 (BEV)	Medium	Low	Medium	Low	4
Scen 1, 70% NF grid	High	Low	Medium	Medium	4
Scen 1, 70% NF grid, low-CI EtOH	High	Low	Medium	High	3
Scen 2a (PHEV-E85 HEV)	Medium	Low	Medium	Low	4
Scen 2a, 70% NF grid	Medium	Low	Medium	Medium	3
Scen 2a, 70% NF grid, low-CI EtOH	Medium	Low	Medium	High	2
Scen 2b (PHEV-CNG)	Medium	Medium	Medium	High	1
Scen 2b, 70% NF grid	High	Medium	Medium	High	2
Scen 3 (E85 PHEV)	High	Low	Medium	Low	5
Scen 3, 70% NF Grid	High	Low	Medium	Medium	4
Scen 3, 70% NF Grid, low-CI EtOH	High	Low	Medium	High	3
Scen 4 (E85 HEV)	Low	Low	Low	Medium	3
Scen 4, Low-CI EtOH	Medium	Low	Low	High	3

7. Conclusions

The purpose of this analysis is to assess vehicle-fuel pathways to dramatically reduce light-duty well-to-wheel greenhouse gas (GHG) emissions by 2050, in the U.S. overall and for the state of California, and to quantify the corresponding impact on vehicle ownership costs and petroleum consumption. For the U.S. analysis, the target GHG reduction is 80% below 2005 levels by 2050 while the California target is 80% below 1990 levels by 2050.

The combination of vehicle fuel efficiency and fuel cycle carbon intensity determine the total GHG emissions in the light-duty transportation sector for a given VMT and fleet size. ***Therefore, maximum reductions will only be achieved with higher efficiency vehicles in conjunction with low-carbon fuels.***

This assessment focused on three primary measures: vehicle efficiency, fuel cycle carbon intensity, and costs. The first step was to determine the projected current and future efficiencies and costs for ICE and advanced vehicle technologies, using both conventional and alternative fuels. From the range of lowest GHG technologies, scenarios were constructed using a fleet turnover model to assess light-duty fleet GHG and petroleum reductions with various combinations of vehicle technologies, fuels, and vehicle sales forecasts.

This study shows that both low-carbon liquid fuels and low-carbon electricity can be effective when coupled with advanced vehicle technologies, but neither is certain to prevail. Both face strong technical, infrastructure, and economic headwinds. This strongly suggests that policies need to encourage the continued development of both pathways, to maximize the likelihood of dramatically reducing GHG emissions in the light-duty transportation sector.

Specifically, the analysis shows that current U.S. and California policies have significant influence over the market penetration of alternative fuels and vehicle technologies, and therefore, on cumulative GHG emissions reductions.

- California's ZEV mandate increases the market share of electric drive vehicles and helps achieve the economies of scale necessary to reduce light-duty BEV prices to be more competitive with ICE vehicles.
- Delays in implementing policies significantly impact the timeline for achieving emissions targets. For example, a 10-year delay in implementing the CAFE/GHG standards would result in an extra 5 billion tonnes[72] of emissions during the analysis period. This is due to the time it takes for new vehicles to penetrate the fleet.
- Policies that advance a reduction in the carbon intensity of fuels could help to reach GHG reduction goals sooner but would provide diminishing returns at greater levels of carbon reduction.

[72] The BEV scenario with low CI fuels reduces GHG emissions by 6.9 billion tonnes. Delaying 10 years reduces this reduction to 1.9 billion tonnes. Depending on the scenario and carbon intensity of fuels, the GHG emissions are increased from 3.6 billion tonnes to 5 billion tonnes with a ten-year delay.

While the focus of this analysis is to 2050, the current period to 2025 will bear significant influence over the evolution and market penetration of vehicle technologies that can achieve substantial GHG reductions for the longer-term. Beyond 2025-2030, fuels become the primary source for significant reductions.

Following are insights that were gained from this study. Rather than a play-by-play recap of the assessment and analysis, these summarize the key findings that emerged.

Even with aggressive alternative vehicle sales starting in 2026, full market penetration of the light-duty fleet will extend beyond 2050. Automakers are projected to rely primarily on ICE technology to meet the proposed 2025 CAFE standards because it is the lowest-cost option. The alternative scenarios for this analysis are implemented starting in 2026. HEV technology is projected to cost more than ICEs with BEV and PHEV costing even more, despite the projection that battery costs will decrease by more than 40% for BEVs and 30% for PHEVs. Accounting for the fact that higher-cost vehicles take longer to enter the market, our assumed nominal technology adoption rates for the US analysis were:

- HEV 11% per year for autos and trucks
- PHEV 7% per year for autos, 3.5% for trucks
- BEV 5% per year for autos, 3% per year for trucks

The slower adoption rates of pricier vehicle technologies, coupled with the large existing legacy fleet, lengthens the time for penetration of these technologies into the fleet.

Table 7-1 compares the scenarios for the U.S. and California markets. Each scenario emphasizes the feasible maximum penetration of a combination of advanced technologies. Although maximum new sales of each advanced technology are very aggressive in 2050, market penetration takes time. Consequently, each technology's share of the total on-road vehicle fleet by 2050 is much lower than its percentage of new vehicle sales. California is projected to have a higher percentage of advanced technology vehicles in the market place by 2025 than the U.S. This gives California a head start in reducing GHG fleet emissions.

Light-duty trucks have vehicle attributes required by some buyers, such as towing or longer vehicle range, that are less suitable for advanced technologies. This limits fleet penetration, resulting in higher average per-vehicle GHG emissions for the light-duty fleet.

Using today's fuels, none of the current and advanced vehicle technologies achieve 80% reduction in GHG emissions. Vehicle GHG emissions can be reduced by increasing the efficiency of an internal combustion engine (ICE) and by increasing the degree of vehicle electrification. With today's fuels—regular unleaded gasoline and today's electricity mix—hybrid electric vehicles (HEVs) are more efficient than ICE-only vehicles, plug-in hybrid electric vehicles (PHEVs) are more efficient than HEVs, and battery electric vehicles (BEVs) without an ICE are the most efficient. Compared to 2016 ICE passenger cars or light-duty trucks, 2050 ICE

Table 7-1. U.S. and California scenario descriptions

Scenario	US Market			California Market		
	2050 Light-Duty Cars Market Share	2050 Light-Duty Trucks Market Share	Percent of Light-Duty Fleet in 2050	2050 Light-Duty Cars Market Share	2050 Light-Duty Trucks Market Share	Percent of Light-Duty Fleet in 2050
Business As Usual (BAU) [73]	85% E10 ICE 1% Diesel 6% E10 HEV 3% E10 PHEV 4% BEV 1% H2 FCV	94% E10 ICE 2% Diesel 1% E10 HEV 1% E10 PHEV 1% BEV 1% FCV	89 1 2 2 3 1	67% E10 ICE 1% Diesel 14% E10 HEV 10% E10 PHEV 5% BEV 3% H2 FCV	85% E10 ICE 1% Diesel 1% E10 HEV 6% E10 PHEV 2% BEV 1% FCV 1% CNG	75 1 10 8 4 2
1. Max BEV/E85 HEV	70% BEV 15% E85 HEV 4.3% E10 ICE All others BAU	45% BEV 45% E85 HEV 4.6% E10 ICE All others BAU	46 26 20 8	70% BEV 14% E10 HEV 2% E10 ICE All others BAU	43% BEV 43% E85 HEV 2% Gasoline ICE All others BAU	50 14 13 22
2a. Max E10 PHEV/E85 HEV	80% E10 PHEV 4.4% E85 HEV 4.3% E10 ICE All others BAU	45% E10 PHEV 45% E85 HEV 4.6% E10 ICE All others BAU	51 21 20 8	75% E10 PHEV 14% E10 HEV 2% E10 ICE All others	45% E10 PHEV 45% E85 HEV 4.6% E10 ICE All others	56 14 E85/10 E10 11 8
3. Max E85 PHEV/E85 HEV	81% E85 PHEV 4.3% E10 ICE All others BAU	45% E85 PHEV 45% E85 HEV 4.6% E10 ICE All others BAU	50 18 21 11	65% E85 PHEV 14% E85 HEV 2% E10 ICE All others BAU	43% E85 PHEV 43% E85 HEV 2% E10 ICE All others BAU	48 E85/8 E10 14 E85/10 E10 11 9
4. Max E85 HEV	81% E85 HEV 4.3% E10 ICE All others BAU	90% E85 HEV 4.6% E10 ICE All others BAU	73 16 11	65% E85 HEV 2% E10 ICE All others BAU	83% E85 HEV 2% E10 ICE All others BAU	62 E85/10 E10 12 16

efficiency increases 36%. By comparison, 2050 HEVs are 57% more efficient than today's ICEs, FCVs 74%, PHEVs 77%, and BEVs 81%. Yet even with these dramatic improvements in efficiency, none of the vehicle technologies alone met the U.S. fleet GHG goal of 86 g CO_2 equivalent/mile.

This is illustrated in Figure 7-1, which shows carbon intensities for current fuels and light-duty auto fuel consumption used in the range of vehicle technologies considered in this analysis—ICE, HEV, PHEV, BEV, and fuel cell vehicle (FCV).[74] The curved line is the level of GHG emissions (86 g CO_2 equivalent/mile) required for the U.S. light-duty fleet to reduce GHG emissions by 80%.

Light-duty trucks are 25% less efficient than passenger cars due to vehicle attributes such as weight and aerodynamics. This makes it even more challenging for any light-duty truck technology to meet the 86 g CO_2 equivalent/mile goal and, more importantly, for the combined light-duty fleet to meet the total reductions in either the U.S. or California.

[73] In the business as usual scenario the percentages of alternative fuel vehicle technologies do not change from 2025 to 2050.

[74] Fuel consumption is directly related to efficiency and the product of fuel consumption and carbon intensity gives GHG emissions in g CO_2 equivalent/mile

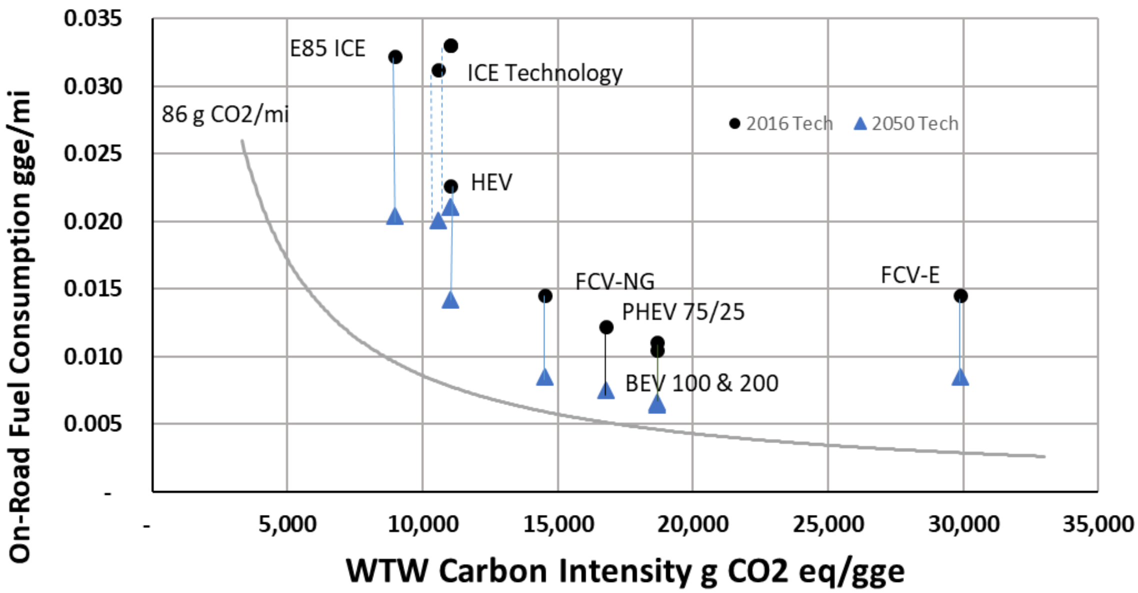


Figure 7-1. Vehicle efficiency alone will not achieve 80% GHG reduction in U.S. light-duty vehicles

Continued fuel efficiency improvements in ICE technology are essential for near-term GHG emission reductions and subsequent transition to low-carbon fuels. ICEs will remain a significant portion of the fleet on roadways to 2025 and beyond. Consequently, their evolution will be a lynchpin in the success of near- and long-term efforts to reduce GHG emissions in light-duty transportation. Delaying the previously proposed 2025 fuel economy standards would likely delay implementing advanced technologies and lower-carbon fuels. A 10-year delay would result in U.S. BAU fleet cumulative GHG emissions increasing by 2.1 billion tonne. Alternative scenarios would increase cumulative GHG emissions by 6 billion tonnes.

Because a major transition takes time and is costlier, automakers are expected to exploit all feasible ICE technologies to improve fuel economy prior to emphasizing vehicle electrification. Consequently, higher-octane fuels can be instrumental in achieving cost effective gains in the near-term, by enabling higher compression ratios and related engine advancements. Ethanol is the most readily available source of octane. More widespread adoption of ethanol then opens the door for expanding the use of low-carbon fuels that are needed for further GHG emissions reductions. Figure 7-2 shows the decrease in carbon intensity as the ethanol blend increases (E30 and E85) and the decreasing fuel consumption (6%) due to higher-compression engines.

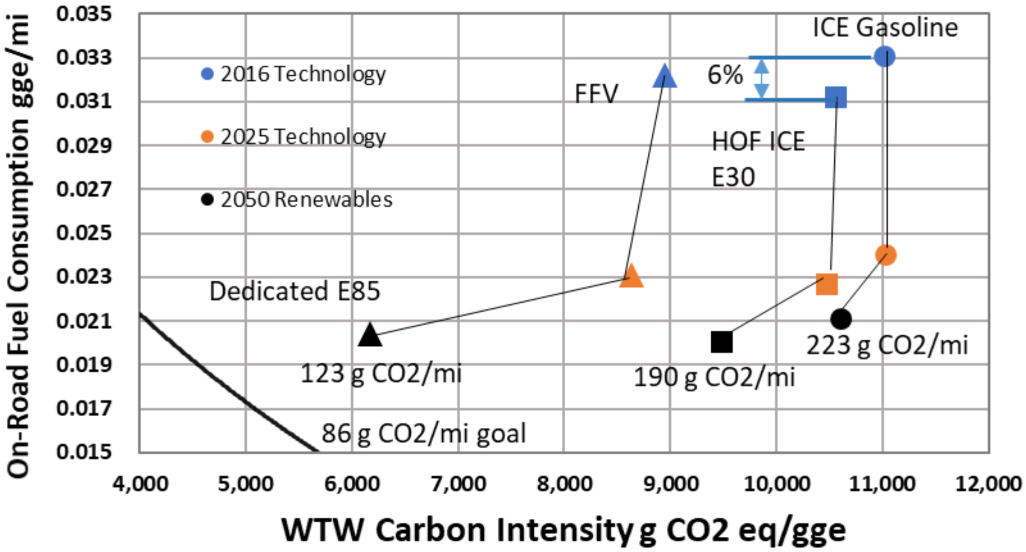


Figure 7-2. ICE technologies reduce GHG emissions but do not achieve fleet goal 86 g/mi CO2e

To meet the 80% reduction goals, lower-carbon fuels and vehicle electrification are needed. As shown in Figure 7-3, advanced vehicle technologies—PHEV and BEV— require low-carbon fuels to achieve the GHG fleet emissions goal for light-duty passenger cars. None of the ICE technologies without electrification meet the goal even with low-carbon E85. HEVs with low-carbon ethanol at 87 g CO_2 equivalent/mile just barely miss the goal.

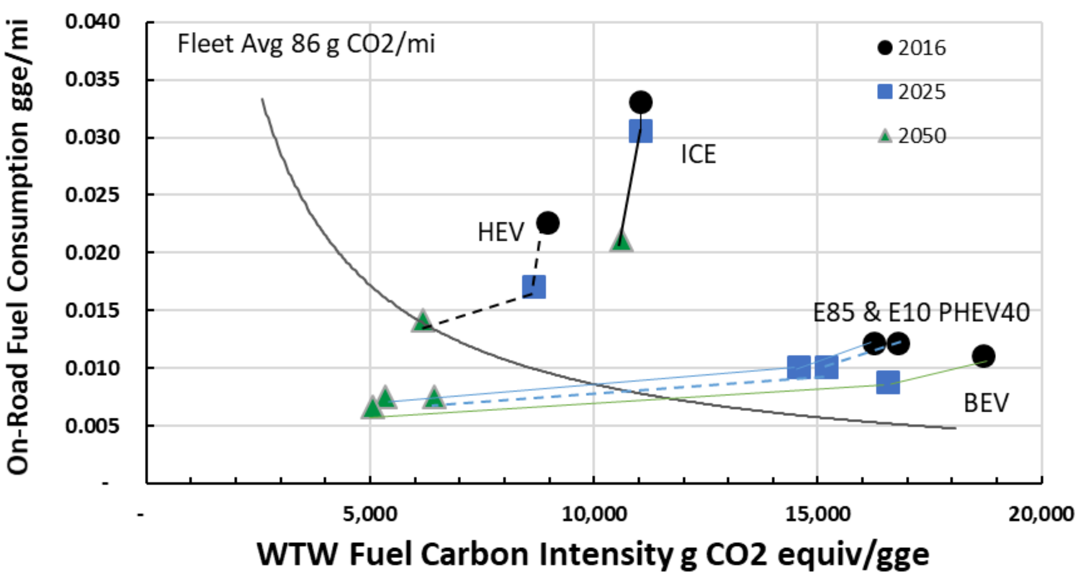


Figure 7-3. Lower carbon fuels and vehicle electrification are needed for U.S. autos to achieve required fleet average GHG emissions

Sufficiently lowering carbon intensity in the fuel supply will be a significant challenge. Fuel carbon intensity varies for each fuel pathway. Today, ethanol is the least carbon-intensive fuel in both the U.S. and California, followed by gasoline and then electricity. In California, electricity is only slightly more carbon-intensive than gasoline due to greater use of low-CI electricity generation and less coal usage.

Lowering electricity carbon intensity to 5,000 g CO_2 equivalent/gge as shown in Figure 7-3, requires the generation mix to be 70% non-fossil and 30% natural gas. For liquid fuels, maximum GHG emission reductions would require a transition from 100% corn ethanol today to a 50% corn-50% cellulosic ethanol for the U.S. and with 66% cellulosic ethanol for California by 2050. Both requirements are challenging. Cellulosic ethanol has still yet to achieve the breakthrough necessary for full-scale commercialization.

This study also briefly analyzed the possible impact of a natural gas to ethanol pathway. The results indicate that the carbon intensity would be roughly comparable to petroleum to gasoline. At worst, this pathway could be more carbon intensive and would therefore negate GHG reduction benefits generated by ethanol’s higher octane.

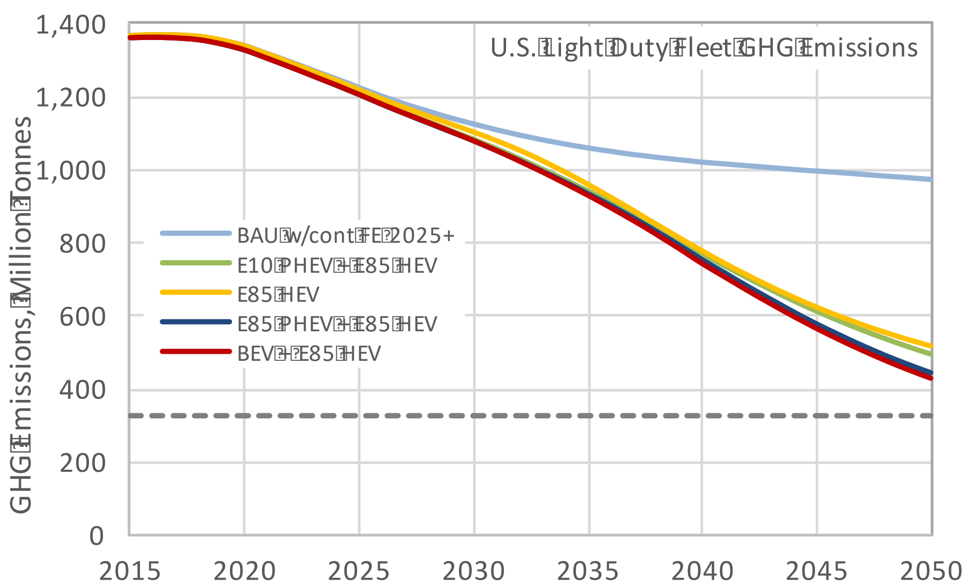
It will be very difficult to reduce light-duty GHG emissions by 80% by 2050. Figure 7-4 shows the U.S. and California light-duty GHG emissions for BEVs, PHEVs and HEVs fueled by low-carbon ethanol and electricity. None of the aggressive alternative fuel scenarios achieve the 80% reduction goals, although the California analysis is closer than the U.S. due to earlier sales of alternative fuel vehicles and low-CI fuels, and differences in fleet characteristics — specifically, higher percentages of automobiles and lower vehicle miles traveled compared to U.S. projections.

In both the U.S. and California, the liquid fuel and battery electric scenarios are virtually tied for the most promising pathways to meet GHG reduction targets as shown in

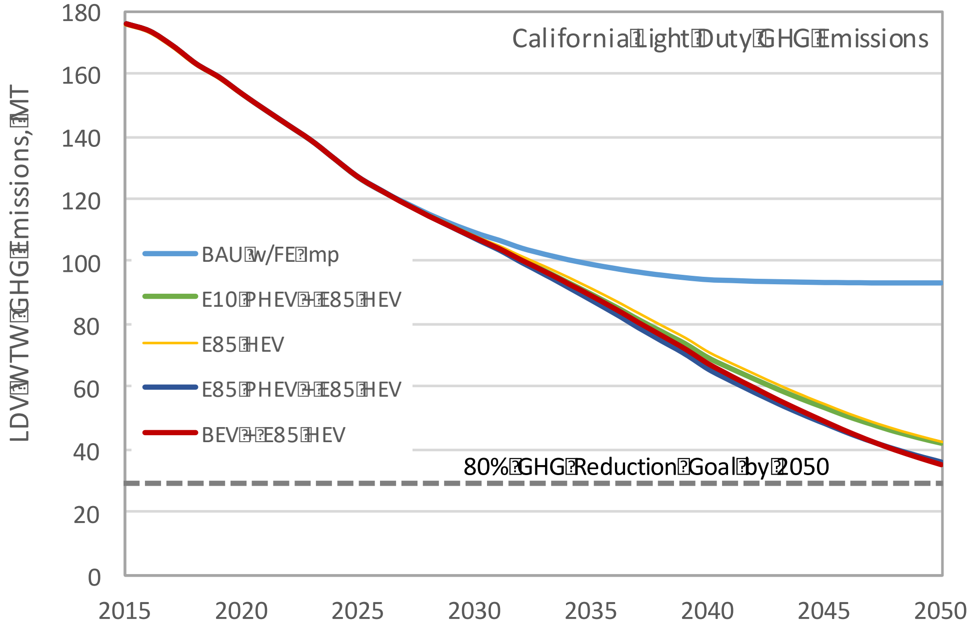
Table 7-2. This is because BEVs, PHEVs and HEVs fueled with low-carbon fuels provide about the same per-vehicle GHG emissions. The addition of low-carbon ethanol and a low-carbon grid has a smaller impact on the California scenarios than the U.S. scenarios because California's baseline carbon intensity is lower to start with.

The results for both the U.S. and California indicate that:

- Low-carbon liquid fuels (in this case ethanol) and low-carbon EV technologies achieve comparable fleet GHG emission reductions
- Low-carbon fuels coupled with efficient powertrain technologies provide the largest fleet GHG reductions
- Vehicle electrification, such as PHEV or HEV technology, will be needed to improve ICE vehicle efficiency



a) Estimated U.S. light-duty fleet GHG emissions with low-CI fuels



b) Estimated California GHG emissions with low-CI fuels

Figure 7-4. Estimated GHG emissions for the U.S. and California analyses

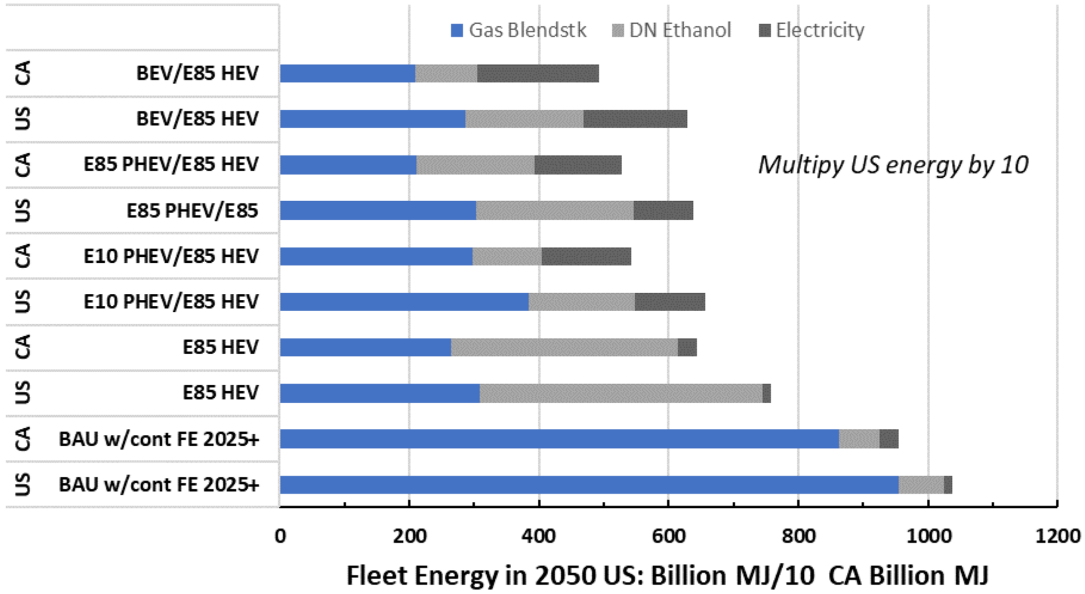
Table 7-2. Comparison of GHG reductions for U.S. and California

Scenario Results for 2050	Light Fleet Fuel Economy mpgge	Base Fuels		Low Carbon Fuels	
		GHG Emissions M Tonnes	Reduction Rel to BAU %	GHG Emissions M Tonnes	Reduction Rel to BAU %
UNITED STATES LIGHT DUTY FLEET					
BAU w/cont FE 2025+	42.5	970	41%	-	-
E85 HEV	57.8	606	63%	521	68%
E10 PHEV + E85 HEV	66.3	598	64%	493	70%
E85 PHEV + E85 HEV	68.3	554	66%	445	73%
BEV + E85 HEV	69.3	571	65%	431	74%
80% Reduction Goal		**330**	**80%**	**330**	**80%**
CALIFORNIA LIGHT DUTY FLEET					
BAU w/cont FE 2025+	44.1	93.2	38%	-	-
E85 HEV	64.5	45.1	70%	42.3	72%
E10 PHEV + E85 HEV	76.4	45.0	70%	42.1	72%
E85 PHEV + E85 HEV	78.1	39.4	74%	35.9	76%
BEV + E85 HEV	83.8	38.8	74%	35.3	76%
80% Reduction Goal		**30.0**	**80%**	**30.0**	**80%**
CA 1990 GHG Emissions	150	million tonnes			
U.S. 2005 GHG Emissions	1650	million tonnes			

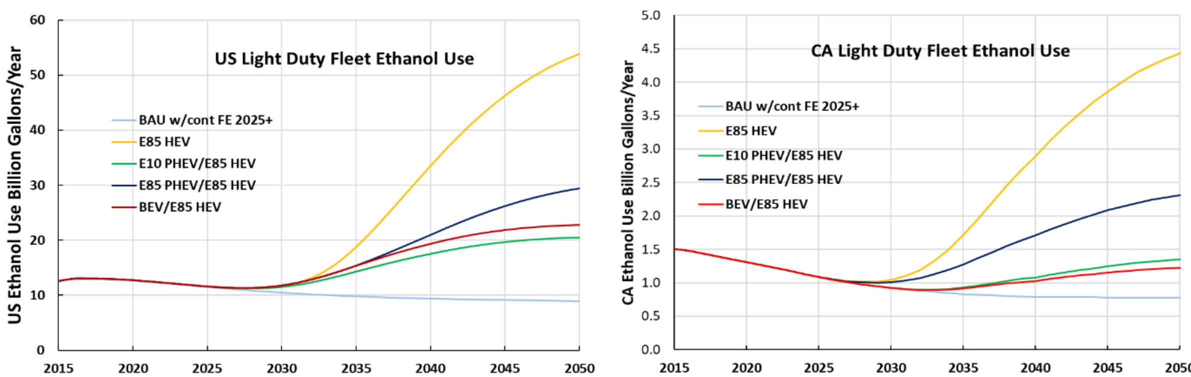
There are several ways that 80% GHG reductions could be achieved:

- Earlier and/or faster penetration of advanced vehicle technologies especially in the light-duty truck segment
- Earlier and/or faster penetration of low-carbon fuels
- Larger percentages of cellulosic or other low-carbon liquid fuels, particularly in the U.S. market
- Delay the GHG target to beyond 2050 to allow for more market turnover of less efficient vehicle technology

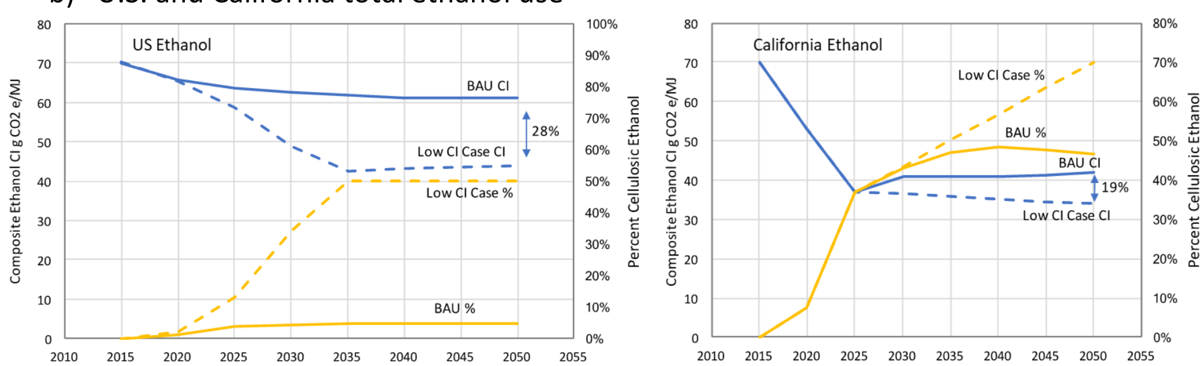
Maximum GHG emissions reductions in liquid fuels will require a major breakthrough in cellulosic ethanol production. Figure 7-5 shows total fuel use, total ethanol use, ethanol carbon intensity and cellulosic percentage shares for the U.S. and California. Total ethanol volumes are highest for the U.S. E85 HEV scenario resulting in over 50 billion gallons a year of ethanol use for the U.S. and 4.4 billion gallons a year for California. A low-carbon ethanol blend could require up to 26.4 billion gallons per year of corn and cellulosic ethanol---significantly higher than current production levels, especially for cellulosic ethanol with only 5.7 million gallons produced in 2017.



a) U.S. and California light-duty total fuel use in 2050



b) U.S. and California total ethanol use



c) U.S. and California cellulosic ethanol use assumed over the analysis period

Figure 7-5. Fleet energy shares, ethanol use, cellulosic percentages and resulting carbon intensity for the U.S. and California analyses

Electricity will need to be much lower in carbon intensity. Electricity carbon intensity for the analysis is shown in Figure 7-6. California's electric grid is cleaner today than the US overall and, in both cases, the low-carbon scenarios are assumed to use 70% non-fossil energy by 2050. The 70% non-fossil electricity needed to substantially reduce GHG emissions will be very challenging to achieve, especially for the U.S. In 2015 the U.S. non-fossil contribution was 36%—this must almost double to 70% in just 35 years. For reference, the impact of the Clean Power Plan proposal would move the non-fossil electricity share from 36% to 42% over the same period. Conversely, California has committed to 50% non-fossil generation by 2030, which is a major improvement in carbon intensity but falls short of the 70% reduction by 2030 necessary to advance climate goals.

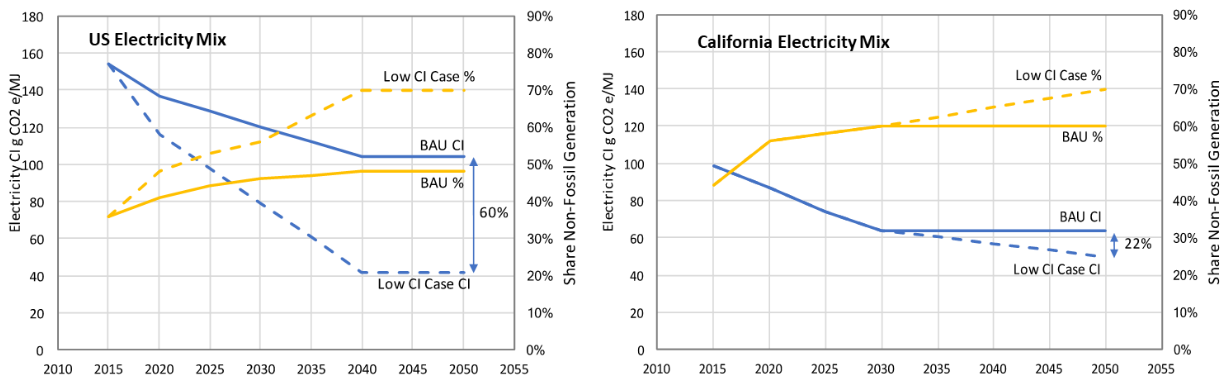


Figure 7-6. Comparison of U.S. and California business as usual and low-carbon electric generation carbon intensities and percent of non-fossil generation

As shown in Figure 7-6 and summarized in

Table 7-3, if the U.S. only achieves 50% non-fossil generation by 2050, carbon intensity increases 2.8 times. This increases the per vehicle BEV GHG emissions from 35 to 95 g CO_2 equivalent/mile, exceeding the fleet average goal of 86 g CO_2 equivalent/mile. With this increase in carbon intensity, the BEV scenario cumulative emissions are reduced by 28% or 1.9 billion tonnes.[75] The impact would be similar for the PHEV scenario, which also relies heavily on electrification.

[75] This was estimated by comparing the cumulative GHG reductions for the BAU to the Low CI case since the CI of the BAU is comparable, i.e. 100 g CO_2 equivalent/mile compared to the 95 g CO_2 equivalent/mile.

Table 7-3. U.S. and California Electricity Carbon Intensities

	Non Fossil Generation %	Carbon Intensity g CO2/gge	BEV GHG Emissions g CO2/mi
	36	18,227	128
	40	17,709	124
US	50	13,628	95
	60	9,546	67
	70	4,936	35
	44	11,718	82
California	60	7,575	53
	70	5,918	41

BEV Fuel Consumption 0.007 mi/gge

Improving vehicle efficiency and replacing gasoline with alternative fuels significantly reduces petroleum consumption. In the BAU case—in which ICE vehicles dominate and fuel efficiency improvement ceases in 2025—petroleum consumption decreases by 23% by 2050, despite an overall increase in vehicle population. With continued fuel efficiency improvement to 2050 (BAU w/cont FE 2025+), petroleum use decreases by 30%. For California, the higher penetration of advanced vehicle technologies and reduced VMT reduces petroleum consumption in 2050 by 43% for BAU and 48% for BAU w/cont FE 2025+. In the U.S. alternative scenarios, maximum penetrations of HEVs, PHEVs, and BEVs reduce petroleum consumption not only by substantially improving fuel efficiency, but also more directly by fueling with electricity or ethanol rather than gasoline. In total, the alternative scenarios reduce petroleum consumption by 71-78% from 2015 levels in the US and by 82-87% in California. All results are shown in Table 7-4.

Table 7-4. Comparison of petroleum reduction for the U.S. and California scenarios

	2050 Petroleum Reduction Relative to 2015			
	U.S.		California	
	Billion gge	%	Billion gge	%
BAU w/cont FE 2025+	35.2	30%	6.7	48%
E85 HEV	88.8	76%	11.8	84%
E10 PHEV + E85 HEV	83.1	71%	11.5	82%
E85 PHEV + E85 HEV	90.0	77%	12.3	87%
BEV + E85 HEV	91.4	78%	12.3	87%

U.S. LD Fleet 2015 Petroleum Consumption 117 Billion gge

CA LD Fleet 2015 Petroleum Consumption 14 Billion gge

GHG emissions reductions are achieved with a simultaneous cumulative cost savings relative to the BAU. The costs per tonne and cumulative GHG reductions for each scenario are shown in Table 7-5. For the U.S. analysis, costs range from a savings of $173 per tonne to a cost of $1 per tonne. The most cost effective is the HEV scenario with E85. However, the addition of cellulosic ethanol reduces cost savings from $173 per tonne to $41 per tonne due to higher fuel costs. The BEV scenario also provides **significant** cost savings (about half the savings of the E85 HEV case). The E85 PHEV scenarios have the highest costs, at $41 per tonne savings with the base fuels and $1 per tonne cost with low carbon fuels. This higher cost again reflects the higher technology cost relative to BEVs and E10 PHEVs and greater use of cellulosic ethanol, especially in the light duty truck segment.[76] Due to their lower technology costs compared to E85 PHEVs, the E10 PHEV scenarios fall between the BEV and E85 PHEV results. Fuel savings for PHEVs are similar to BEVs.

Each low-carbon scenario increases cost per tonne more than the accompanying decrease in cumulative GHG emissions. For example, cost per tonne in the BEV case with low carbon fuels increases by 258% compared to the base fuels case, while cumulative GHG emissions decrease by only 38%.

Table 7-5. U.S. and California cost per tonne of GHG reduced and cumulative GHG reduction

	Base Fuels		Low Carbon Fuels	
	Cost per tonne ($/tonne)	Cumulative Reduction (Billion tonnes)	Cost per tonne ($/tonne)	Cumulative Reduction (Billion tonnes)
U.S.		Billion tonnes		Billion tonnes
BEV/E85 HEV	-85	5.0	-33	6.9
PHEV/E85 HEV	-55	4.7	-13	6.3
E85 PHEV/E85 HEV	-41	5.1	1	6.7
E85 HEV	-173	4.7	-81	5.9
California		Million tonnes		Million tonnes
BEV/E85 HEV	-61	648	-54	682
PHEV/E85 HEV	-33	597	-27	626
E85 PHEV/E85 HEV	-10	667	-4	703
E85 HEV	-128	572	-109	603

California costs per tonne for the base cases are higher than the U.S. while the low CI options have more cost savings than the corresponding U.S. cases. This is due to higher use of low CI fuels and higher electricity prices in the base case for California relative to the U.S. This reduces fuel cost savings and increases cost per tonne. Overall, the cost effectiveness in California ranged from a savings of $128 per tonne to a savings of $4 per tonne. For California, the incremental improvement in GHG emission reductions is much smaller in the low-carbon fuel

[76] Renewable or low CI electricity was assumed to be priced the same as conventional electricity, so electricity prices do not account for increase costs per tonne.

scenarios due to California's aggressive policies to decarbonize transportation fuels and the electricity grid. Like the U.S., all scenarios have cost savings with the HEV E85 scenario having the lowest projected costs per tonne followed by the BEV and then the PHEV scenarios.

These results suggest that substantial GHG reductions may be achieved at lower costs by relying on combinations of liquid-fueled ICE-electric hybridized powertrains and pure electric powertrains.

From our analysis, we draw the following observations:

1. None of the scenarios achieve an 80% reduction in GHG emissions. More time for fleet turnover or faster implementation of lower GHG vehicle and fuel technologies is needed.
2. Improved vehicle efficiencies alone will not provide enough GHG emission reductions. Lower carbon fuels are required, along with higher efficiency vehicles incorporating vehicle platform electrification.
3. Electric vehicle range is important for customer use and acceptance. We believe PHEV with a range of least 40 miles is needed to achieve an electric utilization of 75%. BEVs with at least 200-mile range are needed for large scale penetration into the light-duty vehicle market.
4. The largest GHG reductions cost more for vehicle but are largely offset by fuel savings.
5. Moving from the current petroleum-based gasoline and ICE technologies to renewable ethanol and electricity will be disruptive to the petroleum and electric generating industries. It will also influence the long-term strategies and research and development investments of the auto industry.
6. BEVs provide the largest GHG benefits and considerable consumer costs savings. PHEVs using ethanol or gasoline provide similar benefits but at near breakeven consumer costs.
7. Although this analysis uses the best projections of vehicle technologies and estimates of fuel properties, ultimately the marketplace will decide on the best technology options. Policy, therefore, should encourage and facilitate the use of a variety of fuel pathways that satisfy the fuel economy and GHG standards.
8. For maximum GHG reductions, new passenger car sales need to move quickly to higher efficiency BEVs and PHEVs after 2025. Renewable fuels will also need to transition briskly into the marketplace.
9. New light-duty trucks also need to maximize BEV and PHEV sales but will have to also incorporate HEV technologies coupled with low-carbon fuels to meet the vehicle attributes required in this market segment.
10. Reducing the light-duty GHG emissions by 80% will require that a consistent set of polices in the U.S. and California are adopted that achieve:

a. rapid improvement in ICE technology meeting proposed 2025 fuel economy standards
b. rapid introduction of PHEV and BEV technologies post 2025
c. rapid transition to low-carbon liquid fuels and low-carbon electricity

Appendix A Fuel Economy and Incremental Vehicle Price Forecasts

Two key assumptions in this analysis are projected LDA and LDT fuel economy for the range of technologies considered and their corresponding incremental cost (compared to a MY 2015 gasoline ICEV). Several studies were utilized to inform the development of fuel economy and incremental cost values for the present analysis. These studies include:

- Energy Information Administration Annual Energy Outlook 2016 (AEO2016)
- VISION2015 Default Values (same as AEO2015)
- NAS Transitions Report[77]
- NAS Phase 2 Report[78]
- Argonne C2G Analysis[79]
- Draft MTE (EPA and NHTSA performed separate analyses)[80]
- EPA MTE Technical Support Document[81]
- EPA Fuel Economy Guide[82]
- ARB[83]

Each year, Argonne National Laboratory updates its VISION model with the most recent version of AEO data. At the time this analysis began, VISION2015 with AEO2015 data was available. LCA has updated VISION2015 inputs as described here. The VISION model divides the light-duty sector into two categories: autos and light trucks[84]. The model employs composite new vehicle fuel economy values for these two categories. The composite value is a sales-weighted average (based on AEO2015 sales projections) of corporate average fuel economy (CAFE) certification values by sub-class. Table A-1 provides the AEO2016 market share projections.

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77 Transitions to Alternative Vehicles and Fuels, National Research Council of the National Academies, 2013.

78 "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-duty Vehicles", National Academy of Sciences, 2015

79 Cradle-to-Grave Lifecycle Analysis of U.S. Light-duty Vehicle Fuel Pathways: A GHG Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies, Argonne National Laboratory, June 2016

80 Draft Technical Assessment Report: Midterm Evaluation of Light-duty GHG Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025, U.S. Environmental Protection Agency, California Air Resources Board, National Highway Traffic Safety Administration, EPA-420-D-16-900, July 2016.

81 Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Technical Support Document (EPA-420-R-16-021), November 2016

82 www.fueleconomy.gov

83 California Air Resources Board projection based on EMFAC and VISION2.1 fuel consumption and VMT projections

84 The light truck category includes class 2a (up to 8500 lb GVWR); class 2b trucks are not included.

Table A-1. AEO2016 subclass market share forecasts

Light Auto				Light Truck			
Class	2016	2025	2040	Class	2016	2025	2040
Minicompact	1%	1%	1%	Small Pickup	5%	4%	4%
Subcompact	10%	12%	12%	Large Pickup	23%	23%	23%
Compact	33%	37%	37%	Small Van	1%	1%	1%
Midsize	44%	40%	40%	Large Van	8%	8%	9%
Large	12%	10%	10%	Small Utility	40%	40%	40%
Two Seater	1%	1%	1%	Large Utility	23%	24%	23%

Certification fuel economy is degraded in VISION[85] to reflect on-road performance by a factor of 0.817 for gasoline, diesel, flexible fuel vehicles (FFVs), compressed natural gas (CNG) vehicles and the gasoline portion of plug-in hybrid electric vehicle (PHEV) operation. The degradation factor for hybrid electric and hydrogen fuel cell vehicles is 0.85 while the degradation factor for electric vehicles is 0.70.

The NAS Transitions study developed fuel economy and incremental cost forecasts for LDAs based on the Toyota Yaris (compact), Toyota Camry (midsize), and Chrysler 300 (large car). For the LDT category, fuel economy and cost estimates were developed based on the Saturn Vue (compact SUV), Dodge Grand Caravan (minivan), and the Ford F-150 (standard pickup). We assume here that the average of these three autos is comparable to the AEO2016 light auto category and the average of the three light trucks is comparable to the AEO2016 light truck category. This three-car auto average is thought to be slightly lower than the actual fleet because it emphasizes larger cars. Similarly, the light truck average is likely slightly higher than the actual average because minivans have higher FE than other light trucks and represent much less than 33% of the fleet.

The NAS Transitions forecasts assume that the 2025 CAFE standard is fully implemented in 2030 and then projects that fuel economy continues to improve through 2050 at half the rate of the improvement from 2015-2030. The corresponding costs for this improvement only take into account further light-weighting. The 2030-2050 fuel economy projections seem to be more aspirational rather than a response to market or regulatory drivers. The Argonne C2G study developed fuel economy and cost projections for a midsize auto; it was assumed this could be compared to the AEO2016 LDA category. No projections for light trucks were made.

The Draft MTE provides two different sets of numbers: numbers developed by EPA for compliance with the GHG standard and numbers developed by NHTSA for compliance with the CAFE standard. The EPA analysis provides projected fuel economy for several technologies and a range of vehicle subclasses. LCA utilized the AEO2016 projected subclass sales provided in the table above to estimate composite LDA and LDT fuel economy values. The EPA Draft MTE incremental costs for plug-in vehicles includes the cost of EVSE ($1500). LCA reduced the cost of the EPA plug-in vehicles by $1500. The NHTSA analysis provides composite LDA and LDT fuel economy values and incremental costs.

[85] On-road degradation factors were provided to Argonne modelers by EIA

In November of 2016, EPA issued its proposed MTE Technical Support Document which reflects comments provided by industry and stakeholders on the Draft MTE. Based on comments, EPA revised the vehicle incremental prices for HEVs, PHEVs, and BEVs. The updated incremental prices for 2025 are provided in MTE Tables 2.133 through 2.138. Note that the PHEV and BEV incremental prices include costs for purchase and installation of EVSE; EVSE purchase and installation costs are provided in MTE Tables 2.101-2.104. In the following figures, EPA MTE incremental prices shown for PHEVs and BEVs do not include EVSE costs. Also, the EPA MTE document provides costs for a range of curb weight classes. Incremental prices for curb weight class 3 have been selected as most representative of "light duty auto" used in this analysis while curb weight class 6 has been selected for light truck HEVs. For light truck BEVs and PHEVs, curb weight class 5 values are utilized because heavier towing vehicles are less likely to electrify.

The EPA fuel economy guide (FEG) provides "fuel economy label" values. According to EPA, the label values are 20% lower than certification values. When comparing label values to certification values, a factor of 1.2 has been applied.

ARB fuel economy values are calculated from EMFAC and CA-VISION2.1 projections of fuel consumption and VMT. These calculated values are on-road fuel economy values. These values are divided by the VISION default degradation values to allow comparison with the other certification values. It appears that ARB's future BEV and FCV fuel economy values match the NAS Transitions values[86]; the calculated degradation factor used by ARB is 0.75 rather than 0.70 used by Argonne in VISION.

The following sections compare certification fuel economy and incremental cost projections for LDA and LDT vehicles for the range of technologies considered in the analysis. A summary of the values utilized in the present analysis is provided at the end. Two sets of fuel economy forecasts are utilized: one that maintains fuel economy at 2025 levels for 2025-2050 and another that assumes manufacturers will have to continue to improve their products in 2025-2050 to meet future standards. Specifically, we assume that the ICE improves by 0.5% per year, the HEV improves by 1% per year and that BEV/PHEV/FCV continues at 1.5% per year. It is further assumed that these increases do not have an associated incremental cost but are achieved by increased manufacturing volumes of technology and learning improvements. This assumption is supported by considering the improvements in HEV fuel economy and change in MSRP over time. Figure A-1 provides the Toyota Prius EPA label fuel economy and MSRP from its introduction in 2001 through MY2017. The fuel economy improved by 1.7% per year while the MSRP actually decreased by 0.6% per year.

[86] Phone and email conversations with Kathy Jaw, ARB

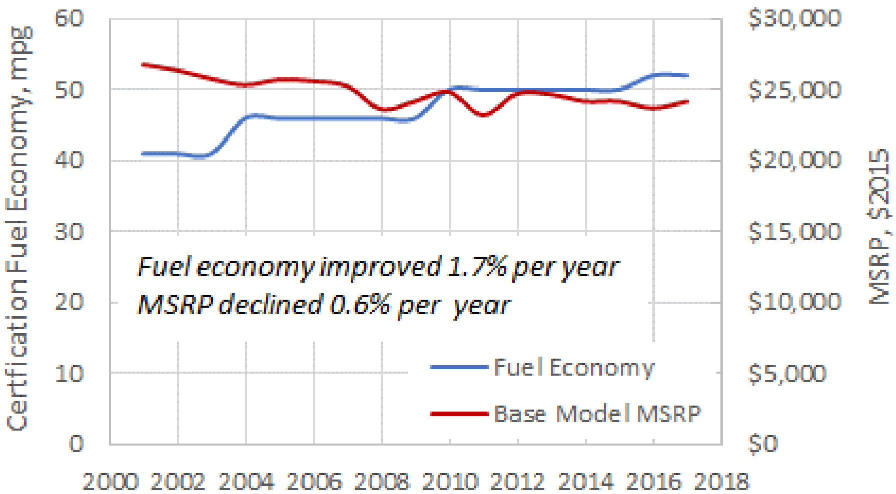

Figure A-1. Toyota Prius EPA Label fuel economy and MSRP ($2015)

Light-duty Auto Fuel Economy and Incremental Cost Forecasts

Figure A-2 provides the various projections for LDA gasoline internal combustion engine (ICE) vehicles. There is close agreement between the various studies through 2025 with the NAS Transitions values higher than the others. This analysis utilizes the AEO2016 projection for the base case fuel economy. Incremental cost relative to a 2015 ICE is provided in Figure A-3. Since the NAS Transitions study assumes that the 2025 standard is fully adopted in 2030, the 2030 incremental cost value agrees will with the 2025 values from the other studies. This analysis assumes a linear increase to the 2025 Argonne C2G and AEO2016 incremental cost value and then flat through 2050.

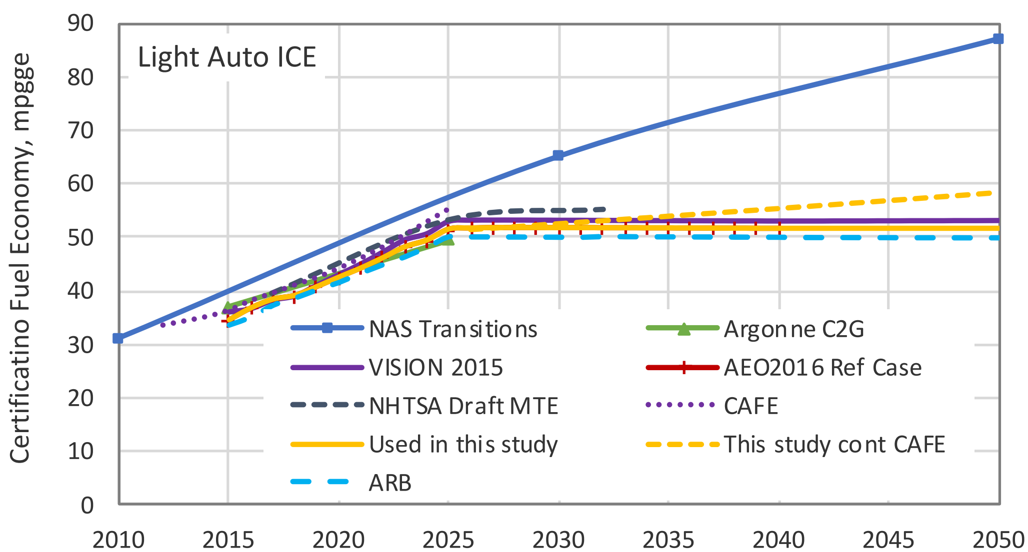

Figure A-2. Certification fuel economy forecasts for LDA gasoline ICE vehicles

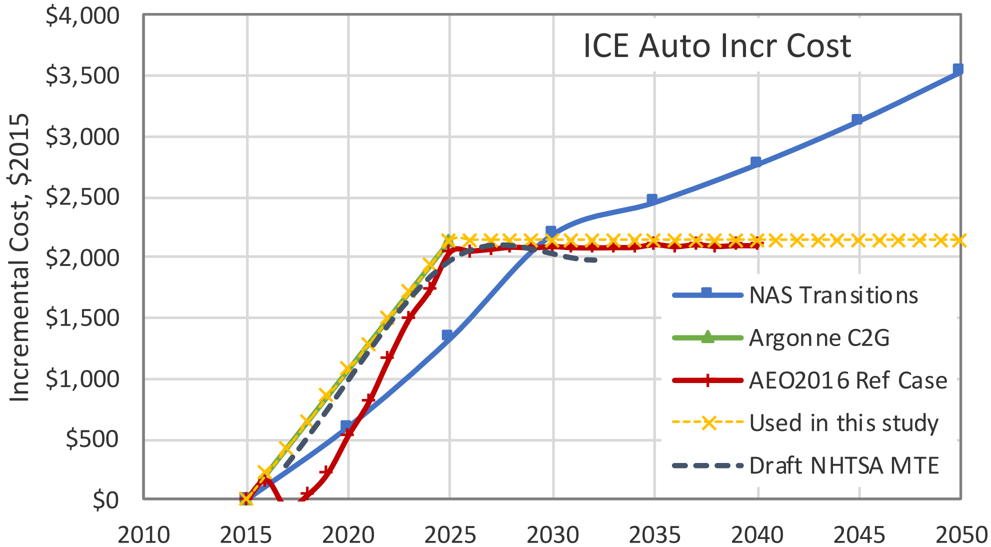

Figure A-3. Incremental cost forecasts for LDA gasoline ICE vehicles

Figure A-4 and Figure A-5 provide the fuel economy and incremental cost projections for LDA diesel vehicles. The NHTSA and ARB fuel economy projections are significantly higher than the others, and seem to have the same slope as the gasoline ICE. Because improvements in gasoline ICE fuel economy are not all translatable to diesel vehicles, LCA has chosen to use the AEO2016/Argonne C2G forecast in this analysis. Since the LDA market shares are extremely low, the impact of this assumption is negligible. Diesel incremental costs are assumed to start at $3,000 currently, increasing linearly to $3,750 in 2025 and remaining constant thereafter. Because diesel vehicle shares are not increased in any of the scenarios considered, the incremental cost assumption does not impact the analysis.

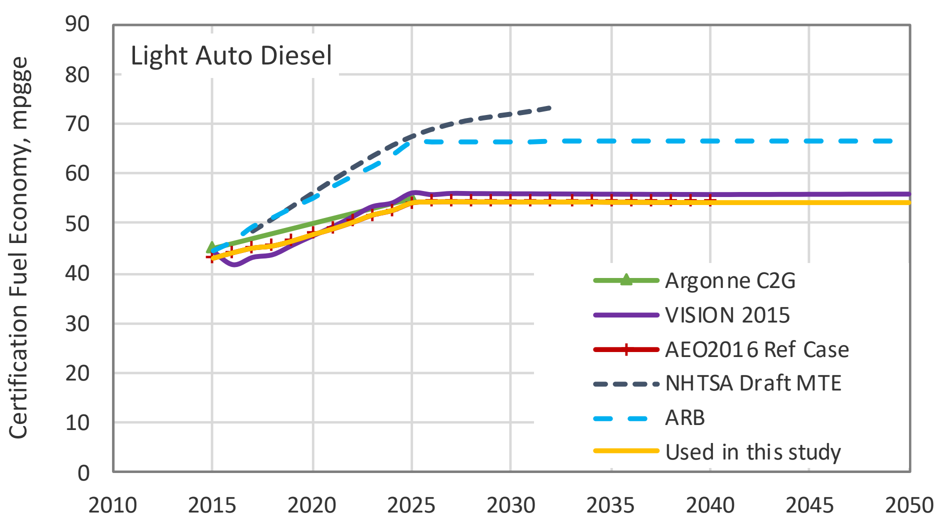

Figure A-4. Certification fuel economy forecasts for LDA diesel vehicles

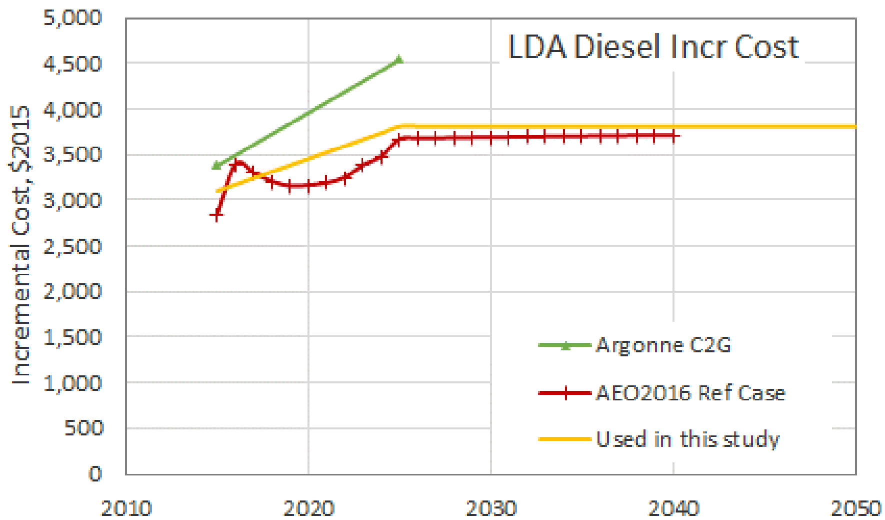

Figure A-5. Incremental cost forecasts for LDA diesel vehicles

For ethanol FFVs, the default energy economy ratio (EER) utilized in VISION2015 is 1.01 for operation on both E10 and E85. EER is the ratio of alternative vehicle fuel economy to base vehicle fuel economy. A review of new vehicle fuel economy ratings[87] for light autos indicates that the current EER for operation on E85 is 1.03. We have modified the VISION model such that the EER on gasoline is 1.0 and the EER on E85 is 1.03 for light autos and light trucks. The cost associated with adding fuel flexibility is assumed to be $100 for light autos and $125 for light trucks (NAS Phase2 report). A 30% manufacturer markup is added with an additional 16% dealer markup.

The EPA Fuel Economy Guide and vehicle manufacturer websites were utilized to generate the plot of incremental vehicle price vs EER for gasoline hybrid electric vehicles (HEVs) in Figure A-6. The average current EER is 1.4; this was applied to the current average gasoline ICE certification fuel economy to arrive at the 2016 HEV value used in this analysis (52 mpg). Excluding the two luxury models (Acura RLX and Nissan Murano), the current average incremental cost is $4,480. If the two luxury models are included, the average increases to $5,580. LCA believes the sales weighted average incremental cost is likely closer to the $4,480 estimate.

[87] US DOE and US EPA Fuel Economy estimates, www.fueleconomy.gov

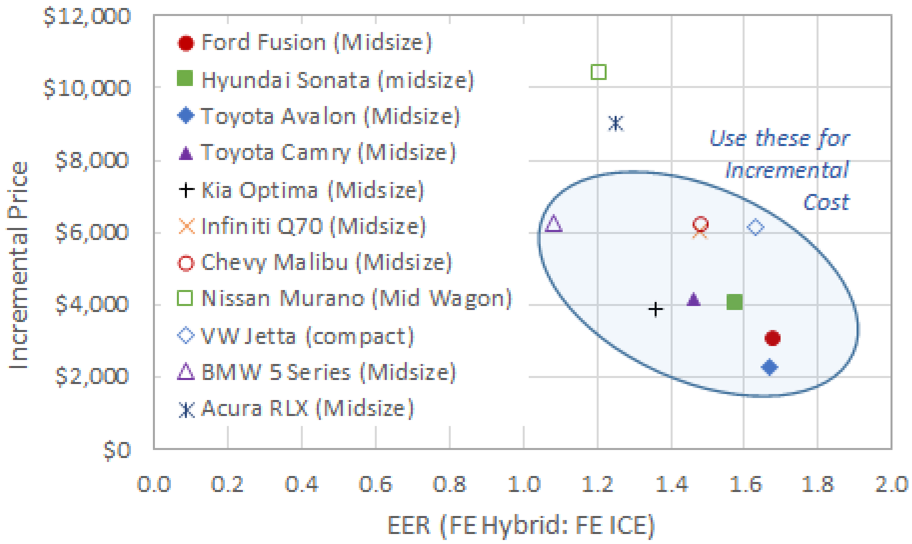

Figure A-6. Current EER and incremental cost for LDA HEVs

The certification fuel economy forecasts for LDA HEVs are summarized in Figure A-7. The average MY2016 value from the Fuel Economy Guide (corrected to certification fuel economy values) matches all the estimates except for the NHTSA Draft MTE values which actually decrease from 2017-2025. For 2017, NHTSA assumed 43% of sales would be Toyota Prius with a fuel economy of 77 mpg (the 2016 Prius certification value is ~ 62 mpg). In this analysis, LCA has utilized the AEO2016 forecast. The Argonne C2G estimates are also slightly higher in 2025, but their 2025 estimates assume full commercialization (>500,000 units). If full commercialization is delayed to 2030 then their results are line with the other estimates.

Figure A-8 provides a comparison of the LDA HEV incremental cost forecasts. The MY2016 incremental price is similar to both the EPA and NHTSA Draft MTE estimates, and lower than the Argonne/AEO2016 estimate. We expect the Argonne costs to be higher since their analysis covered only a midsized vehicle and apparently AEO2016 over estimated costs. The NHTSA draft value and the EPA MTE draft and final values are lower than the Argonne/AEO values, and their 2016 values are consistent with the current market offerings. For this analysis, we start at the current market increment, follow the Draft EPA and NHTSA MTE curves to the EPA MTE 2025 value, cross the NAS Transitions value in 2027 and maintain the increment at $3000 through 2050.

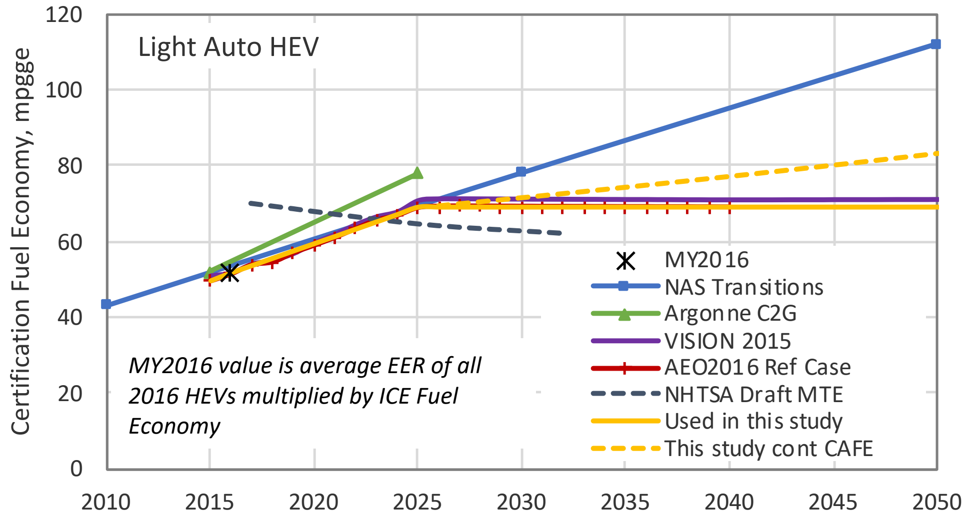

Figure A-7. Certification fuel economy forecasts for LDA HEVs

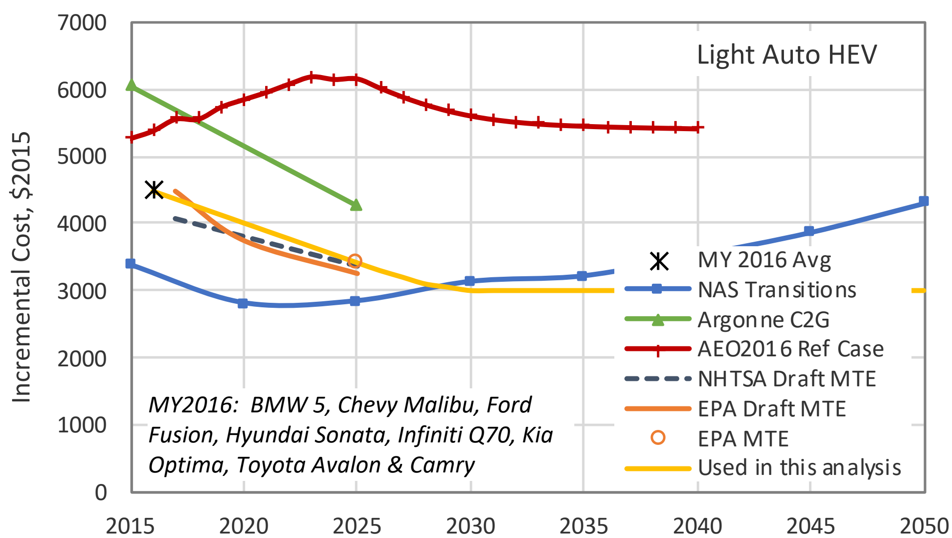

Figure A-8. Incremental cost forecasts for LDA HEVs

For battery electric vehicles (BEVs) with 100-mile range, Figure A-9 provides current EPA fuel economy label data (20% lower than certification value). Excluding the Mercedes (much lower fuel economy and lower sales), the average fuel economy label is 113 mpgge which corresponds to ~ 136 mpgge certification. Four of these vehicles have ICE counterparts; by comparing to the ICE versions, EER and incremental price is calculated and provided in Figure A-10. The average EER is 3.8 which corresponds to a certification fuel economy of 138 mpgge when applied to the 2016 ICE average value. The average incremental price is $12,750.

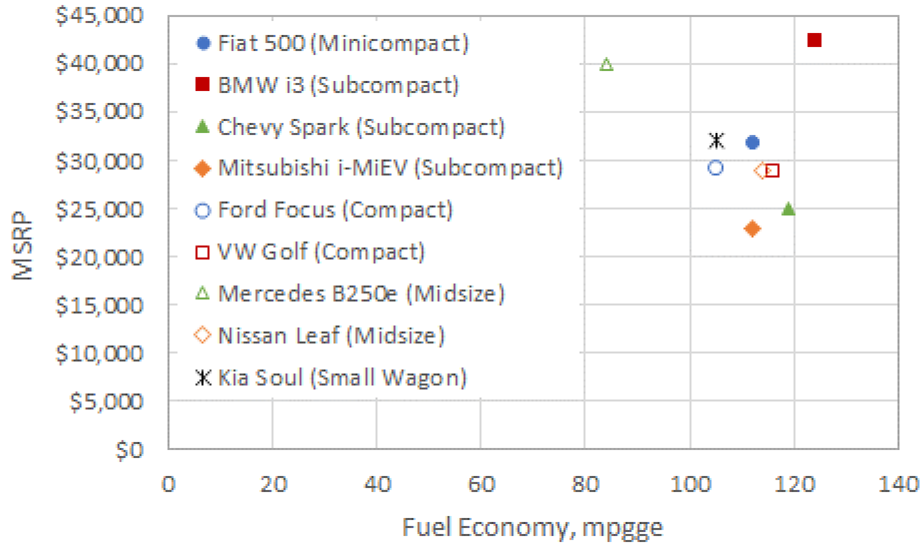

Figure A-9. MY2016 BEV100 MSRP vs EPA fuel economy label

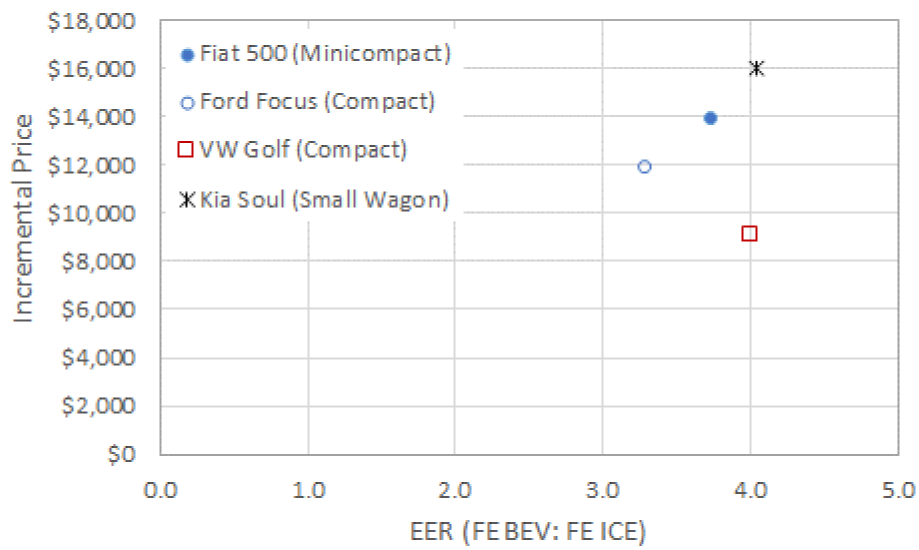

Figure A-10. MY2016 BEV100 incremental cost vs EER

The BEV100 certification fuel economy projections are summarized in Figure A-11. The MY2016 value (136) is much lower than the NAS Transitions and ARB estimates and slightly lower than Argonne C2G and AEO2016 values. The ARB values shift to the NAS Transitions values for 2025-2050. These estimates appear too optimistic based on current technology. The VISION2015 estimates agree with current technology but show little improvement with time which seems unreasonable. For this analysis, we utilize the MY2016 value and increase along the slope of the Argonne C2G, AEO2016, and NAS studies through 2025. The dashed yellow line indicates the values for 2025-2050 used if regulatory pressure on fuel economy continues. Because there is significant disagreement, a sensitivity case is run in which the fuel economy in 2016 is the current average value, but the 2025 value is the same as the Argonne C2G and AEO2016 value (172 mpgge).

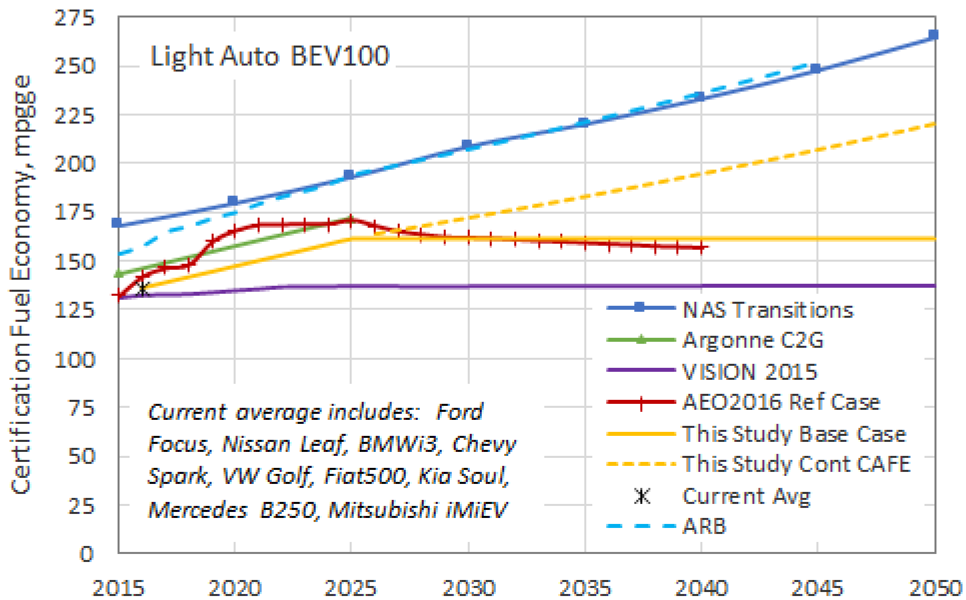

Figure A-11. Certification fuel economy forecasts for LDA BEV100

Incremental cost forecasts are provided in Figure A-12. The MY2016 increment ($12,750) is consistent with the EPA Draft MTE estimate (without charger), about 5% higher than the NAS and Argonne estimates, and approximately 30% lower than the AEO2016 estimate. NHTSA's MTE analysis does not provide a BEV100 cost increment. EPA's final MTE increment for 2025 is lower than the draft value. For this analysis, LCA utilizes the current market value for 2016, decreases linearly to the final EPA MTE 2025 value and then levels out at $6,500 through 2050. The 2016 value appears conservative (higher) relative to the NAS and Argonne projections though significantly lower than the AEO2016 value. It is possible that the incremental cost could decrease to the NAS/Argonne levels, but unlikely that they would increase to the AEO2016 levels. As a sanity check on these values, LCA performed an analysis of battery pack and drive train costs as a function of projected production volume using Argonne National Laboratory's BatPaC model. The projected values were consistent with MTE values.

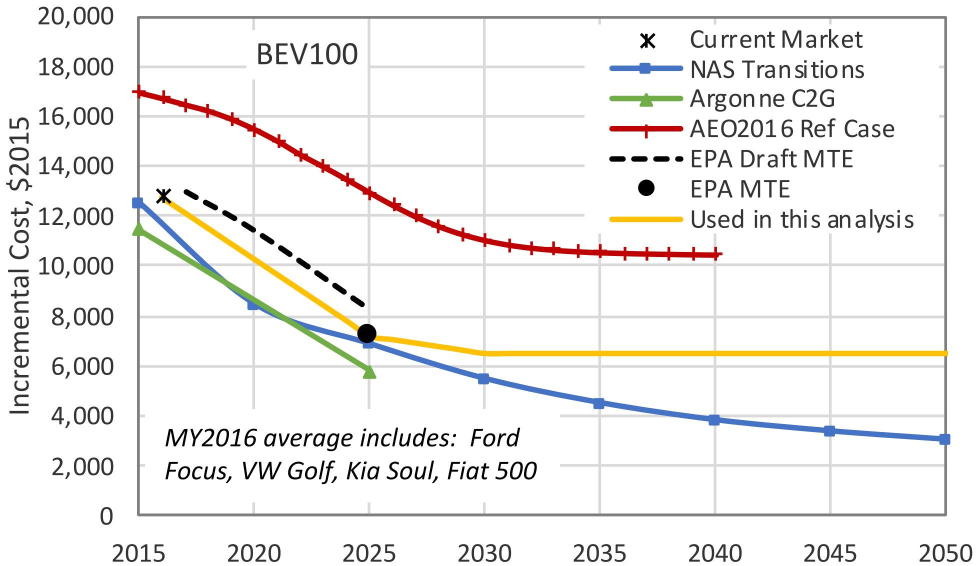

Figure A-12. Incremental cost forecasts for LDA BEV100

For the BEV with 200+ mile range (BEV200), certification fuel economy forecasts are provided in Figure A-13. There are two Tesla models on the market with over 200-mile range, one with a 70-kWh battery and one with a 90-kWh battery. The NHTSA value is based on the Tesla model with more range (93 mpgge EPA label corrected to 116 mpgge certification) and projects minimal improvement over time. The Tesla value is valid for 2016, but new non-luxury (smaller) models will enter the market with higher fuel economy. In fact, the Chevy Bolt, introduced in early 2017, has a 238-mile range and an EPA label fuel economy of 119 mpgge (143 certification).

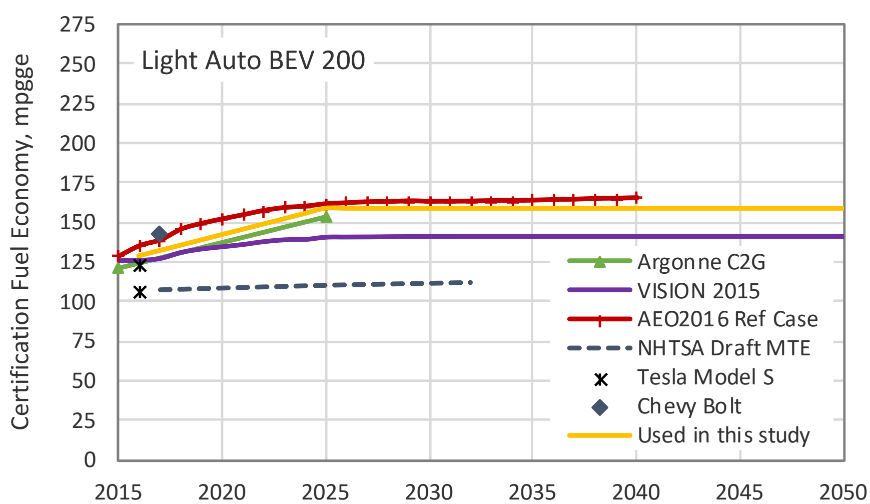

Figure A-13. Certification fuel economy forecasts for LDA BEV200

For the present analysis, LCA has utilized the BEV100 fuel economy and added a penalty for the increased battery weight. To estimate the BEV200 fuel economy, we assume 233 Wh/kg battery weight[88], 30 kWh for the BEV100 and 60 kWh for the BEV200, a 3000 lb vehicle and 5.2% fuel economy penalty for every 10% change in vehicle weight[89]. The result is a 4.9% fuel economy penalty for the BEV200 relative to the BEV100. This forecast results in certification fuel economy estimates of 129 mpgge in 2016 and 158 mpgge by 2025. The 2016 analysis value is lower than the MY2017 Chevy Bolt (certification 143 mpgge), but the Bolt is a small car and does not necessarily represent a fleet average value.

BEV200 incremental cost forecasts are provided in Figure A-14. There are two groups: Argonne, NHTSA Draft MTE, and AEO2016 with very high incremental cost and the EPA MTE (draft and final) and NAS Transitions (estimated by doubling the battery costs for the BEV100) significantly lower. The Argonne/NHTSA/AEO2016 value is ~ 4 times higher than the BEV100 increment. If price is based on $125/kW battery cost and doubling capacity, the increment is like the EPA Draft MTE price. Moreover, the Chevy Bolt has a lower MSRP ($37,495) than the Argonne/NHTSA ***increment***, indicating that the lower estimate is much more in line with actual incremental costs. For this analysis, an initial incremental price halfway between the NAS and EPA Draft MTE values is selected, decreasing to the EPA final MTE increment in 2025. The incremental price continues to decrease to $8800 in 2030 and remains at this level through 2050, crossing the NAS Transition curve in 2040.

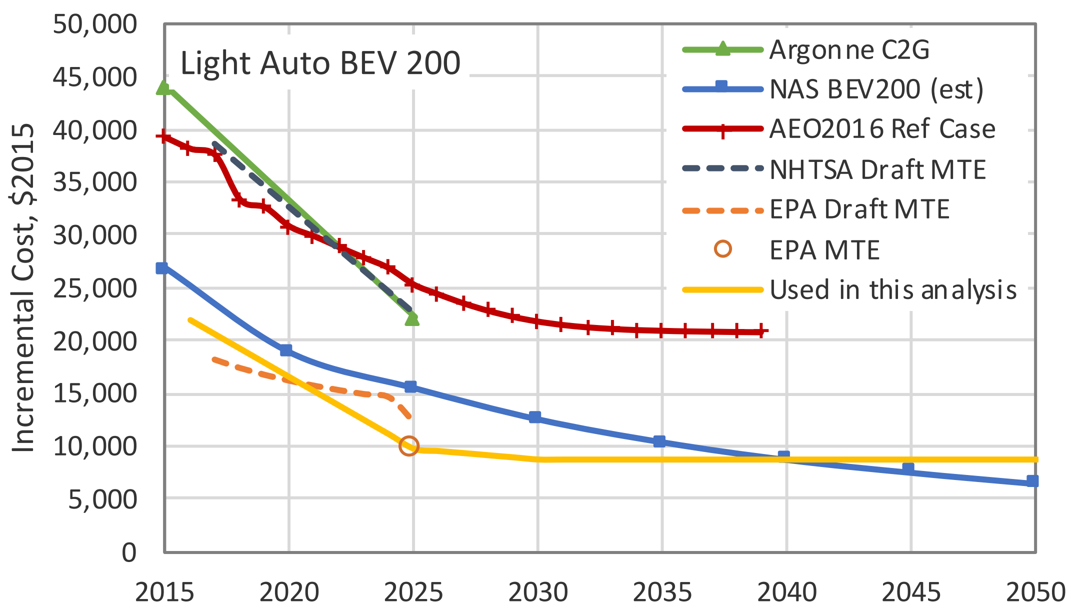

Figure A-14. Incremental cost forecasts for LDA BEV200

[88] https://cleantechnica.com/2015/03/17/lighter-batteries-may-prove-tipping-point-electric-vehicles/
[89] EPA Draft MTE

A reduction in battery pack cost was run as a sensitivity test. The values for vehicle incremental cost as well as battery pack cost are provided in Table A-2 for LDA (class 3) and LDT (class 5). The EPA battery pack costs range from $4,700 to $7,800 with corresponding incremental vehicle costs ranging from $7,160 to $12,181. The battery pack costs range from 115 to 159 $/kWh. Many analysts are predicting that battery pack prices will decrease to the benchmark level of $100 per kWh by 2025. Therefore, this sensitivity test considers battery pack costs of $100 per kWh; Table 5-6 provides the incremental vehicle costs for a $100 per kWh battery pack based on EPA's MTE incremental cost estimates. A comparison of the base case and sensitivity case prices is provided in Table A-2 and illustrated in Figure A-15 and A-16.

Table A-2. Incremental BEV price as a function of battery cost

Vehicle	Weight Class	EPA MTE BEV Costs MY2025					Costs at $100 /kWh		Change %
		Battery Pack DMC[1] $2015	$/kWh	kWh (calc)	Vehicle Inc Cost[2] $2015	Vehicle Inc Less Bat Pack	Battery Pack DMC $2015	Vehicle Inc Cost $2015	
BEV-100	LDA	4,693	159	29.5	7,160	2,467	2,952	5,419	-24%
BEV-100	LDT	6,460	133	48.6	9,768	3,308	4,857	8,165	-16%
BEV-200	LDA	5,998	146	41.1	9,663	3,665	4,108	7,773	-20%
BEV-200	LDT	7,828	115	68.1	12,181	4,353	6,807	11,160	-8%

DMC = Direct Manufacturing Cost
1.EPA MTE Table 2.118 and Table 2.119
2.EPA MTE Table 2.137 and Table 2.138

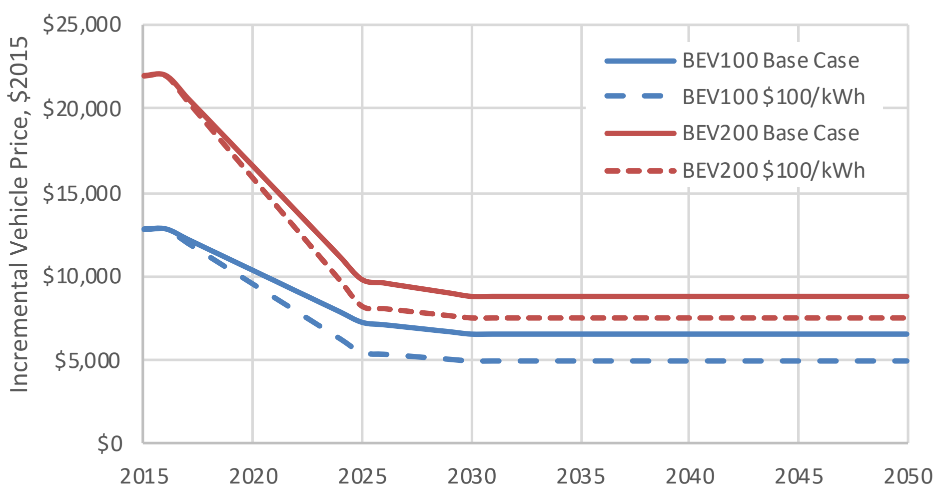

Figure A-15. LDA BEV base case and sensitivity case incremental price

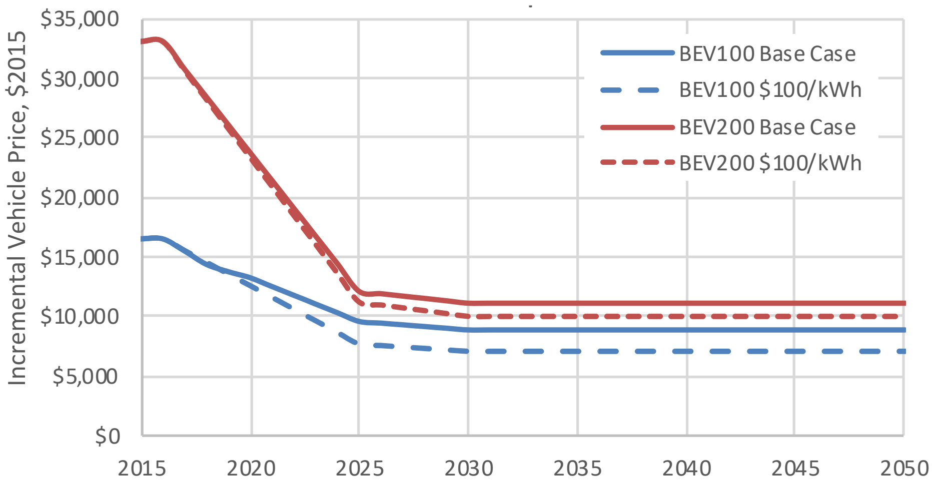

Figure A-16. LDT BEV base case and sensitivity case incremental price

There are currently 9 plug-in hybrid electric vehicles (PHEVs) on the market; their electric mode fuel economy (EPA label) and MSRP are provided in Figure A-17. The current average fuel economy is 84 mpgge (101 mpgge certification). Of the current offerings, 6 models have gasoline counterparts (Figure A-18), so EER and incremental cost can be calculated. Based on these 6 models with gasoline counterparts, the average electric mode EER is 3.1 which corresponds to a certification fuel economy of 112 mpgge, lower than the BEV100 (136 mpgge, certification). However, this EER value is based on a small sample size and does not include one of the market leaders, the Chevy Volt. An EER for the Volt can't be calculated because it doesn't have a gasoline equivalent; its electric mode certification fuel economy is 127 mpgge. For this analysis, we assume the PHEV electric mode fuel economy is the same as the BEV100. This assumption is consistent with the NAS transitions, Argonne, and other forecasts.

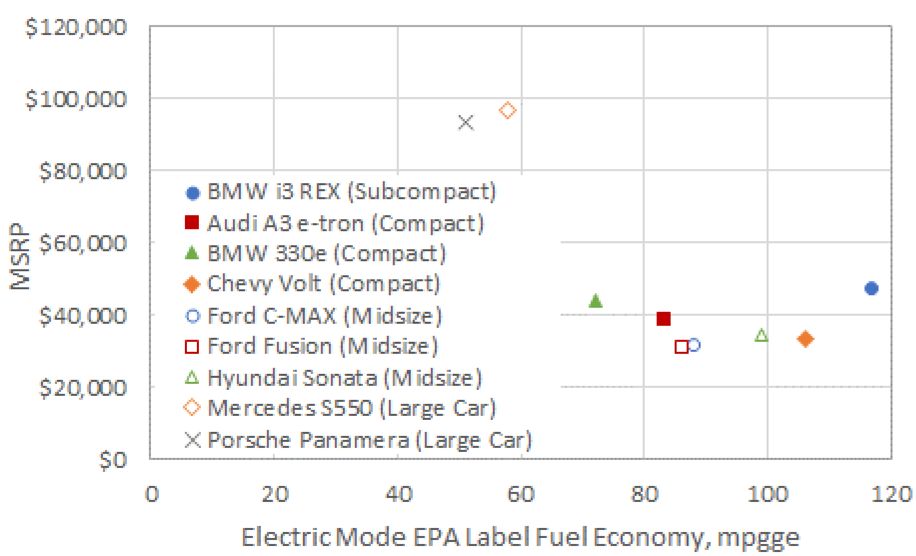

Figure A-17. MY2016 LDA PHEV electric mode EPA label fuel economy and MSRP

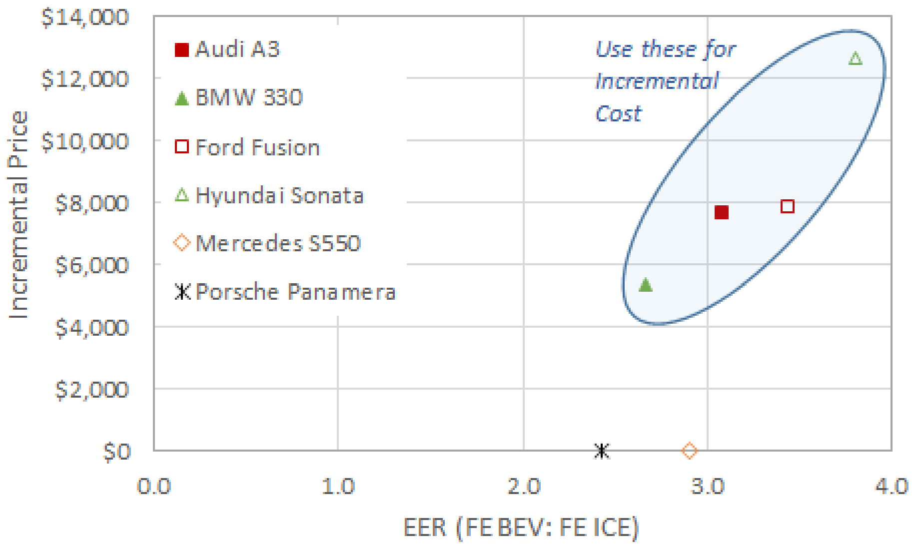

Figure A-18. Incremental cost vs EER for MY2016 LDA PHEV

Figure A-19 provides the various PHEV electric mode certification fuel economy forecasts. The VISION2016 value is significantly lower than the other projections. The Argonne C2G and NHTSA Draft MTE values are like the BEV100 assumption. The NAS and ARB (same as NAS) forecasts are the same as their corresponding BEV100 values. The forecast used in this analysis is generally consistent with Argonne C2G and NHTSA. Note that the MY2016 value shown in the figure is based on the EER calculated from current vehicles with gasoline counterparts – as discussed above, this omits the Chevy Volt with certification fuel economy of 127 mpgge.

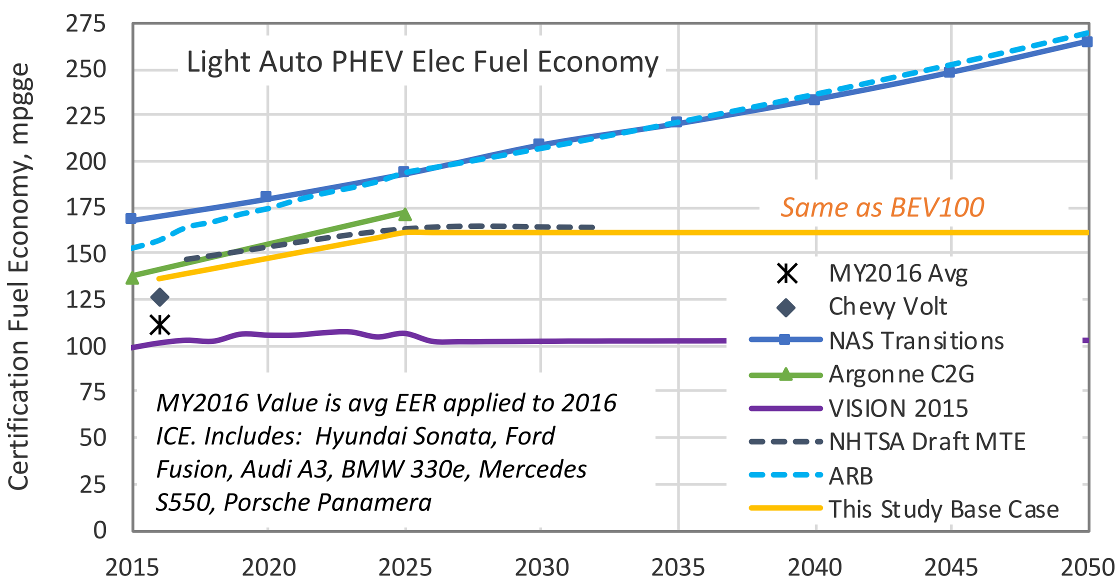

Figure A-19. Certification fuel economy (electric) forecasts for LDA PHEV

The current average PHEV MSRP is $50,000 (Figure A-17). The average MY2016 incremental cost (omitting the Mercedes and Porsche) is $8400 (Figure A-18). Incremental cost forecasts are summarized in Figure A-20 along with the MY2016 incremental cost. For this analysis, incremental price starts at the EPA Draft MTE incremental price, decreases to $9,500 in 2025, and levels out at $8,600 in 2030. The MY2016 incremental cost is low possibly because the electric range of the vehicles considered is approximately 20 miles or less (larger all electric range requires more battery capacity and increases cost). This analysis assumes PHEVs quickly move to 40 miles of electric range.

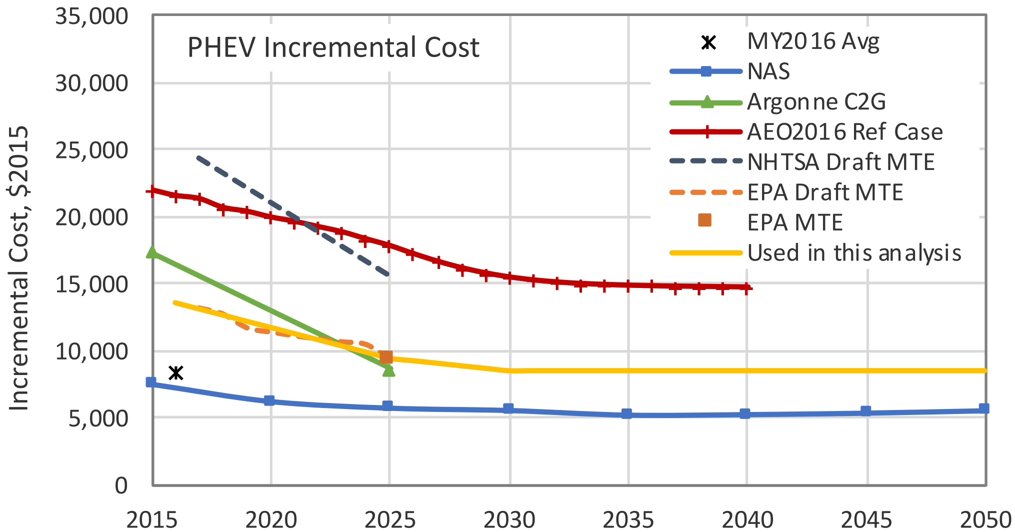

Figure A-20. Incremental cost forecasts for LDA PHEV

For hydrogen fuel cell vehicles (FCVs), the Argonne C2G and ARB/NAS Transitions fuel economy forecasts (Figure A-21) are very close to the current model on the market (Toyota Mirai). The AEO2016 values are surprisingly low. For this analysis we follow the Argonne values to 2025. For incremental cost (Figure A-22), this analysis starts at the current value and decreases along the NHTSA Draft MTE line through 2025, continuing linearly through 2045 when it hits the Argonne C2G mature value. Because this analysis does not consider high volumes of FCVs over the analysis period, economies of scale are not fully achieved until 2045.

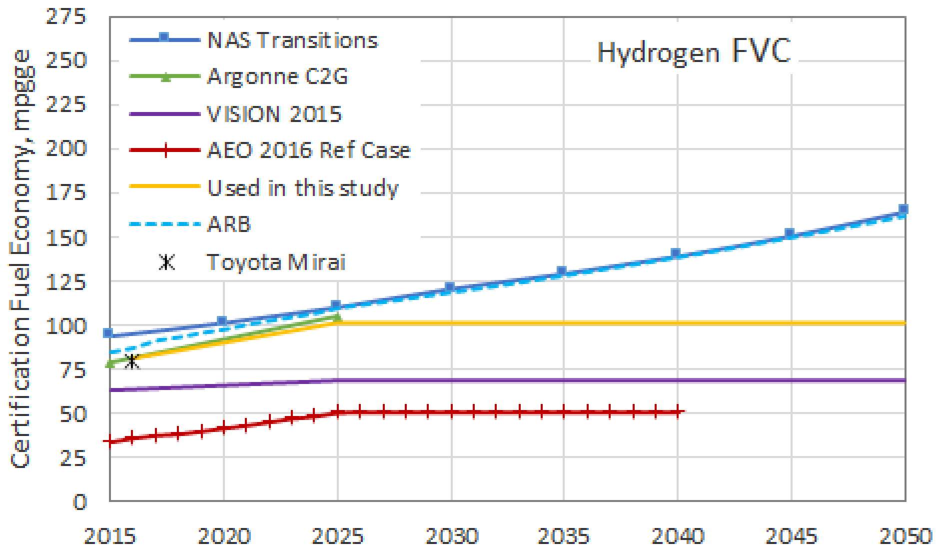

Figure A-21. Certification fuel economy forecasts for LDA H2 FCV

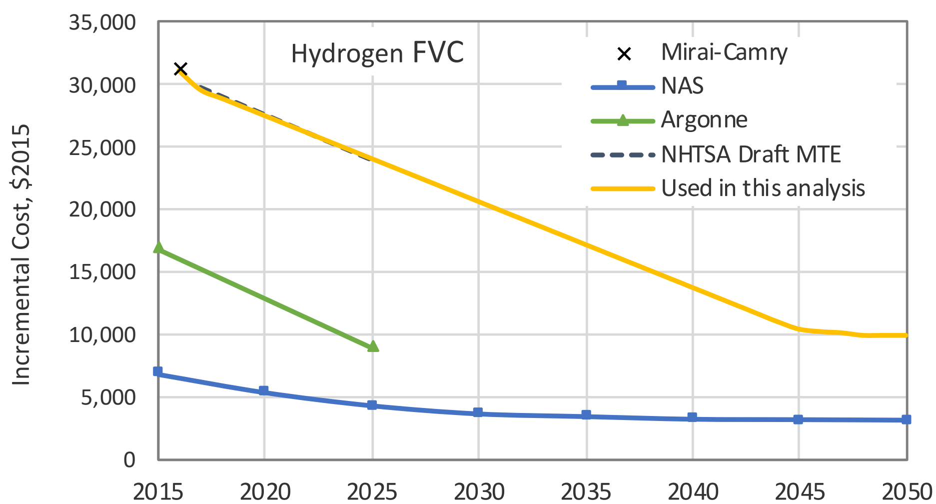

Figure A-22. Incremental cost forecasts for LDA H2 FCV

A summary of the light auto certification fuel economy and corresponding EER values used in the analysis are provided in Table A-3. The EER values are relative to the gasoline ICE in the year considered, for example, the 2025 EER value is the alternative fuel vehicle fuel economy in 2025 divided by the gasoline ICE fuel economy in 2025. Also provided is the annual average improvement for the 2016-2025 period and the 2025-2050 period. Note that most of the fuel economy improvement occurs before 2025 except for the electric drive technologies. The electric drive vehicles experience the most improvement in fuel economy between 2016-2025 and this improvement continues at only a slightly lower rate through 2050.

Table A-3. Summary of LDA certification fuel economy and EER analysis values

	Certification FE, mpgge			EER			Change, mi/gal/yr	
	2016	2025	2050	2016	2025	2050	2016-2025	2025-2050
Gasoline ICE	37	51	58	1.00	1.00	1.00	1.6	0.3
Diesel	44	54	62	1.21	1.06	1.06	1.1	0.3
FFV-Gasoline Mode	37	51	58	1.00	1.00	1.00	1.6	0.3
FFV-EtOH Mode	38	53	60	1.03	1.03	1.03	1.7	0.3
Gasoline HEV	52	69	83	1.42	1.35	1.43	1.9	0.6
PHEV-Gasoline Mode	52	69	83	1.42	1.35	1.43	1.9	0.6
PHEV-Electric Mode	136	162	221	3.71	3.16	3.80	2.9	2.4
BEV-100	136	162	221	3.71	3.16	3.80	2.9	2.4
BEV-200	129	158	216	3.53	3.09	3.72	3.2	2.3
Hydrogen FCV	81	101	138	2.22	1.97	2.37	2.2	1.5

Table A-4 summarizes the values used in the analysis for incremental LDA cost. The gasoline and diesel vehicles experience rising costs through 2025 while the other technology costs decrease dramatically. Note that the hydrogen FCV has much higher incremental cost through 2025 than the next most expensive technology (BEV200), with a significantly worse fuel economy.

Table A-4. Summary of LDA incremental costs (relative to 2015 gasoline ICEV)

	Incremental Cost, $2015			Annual Change	
	2015	2025	2050	2016-2025	2025-2050
Gasoline ICE	0	2,149	2,149	215	0
Diesel	3,100	3,800	3,800	70	0
Gasoline HEV	4,484	3,416	3,000	-107	-17
PHEV	13,500	9,500	8,600	-400	-36
BEV-100	12,800	7,200	6,500	-560	-28
BEV-200	22,000	9,800	8,800	-1,220	-40
Hydrogen FCV	31,190	24,159	10,000	-703	-566

Light Truck Fuel Economy Projections

Certification forecasts for light truck gasoline ICEVs are summarized in Figure A-23. Like the LDA, all the forecasts agree, with the NAS Transitions estimate slightly higher than the rest. The incremental cost forecasts are provided in Figure A-24. The NAS study assumes the 2025 standard is fully adopted in 2030, so its 2030 incremental cost is like 2025 estimates of the others. The NHTSA MTE value is lower than the AEO2016 estimate for 2025. This analysis assumes a linear increase to the midpoint between the NHTSA and AEO2016 values, which is essentially the NAS Transitions 2030 value (which should actually be 2025).

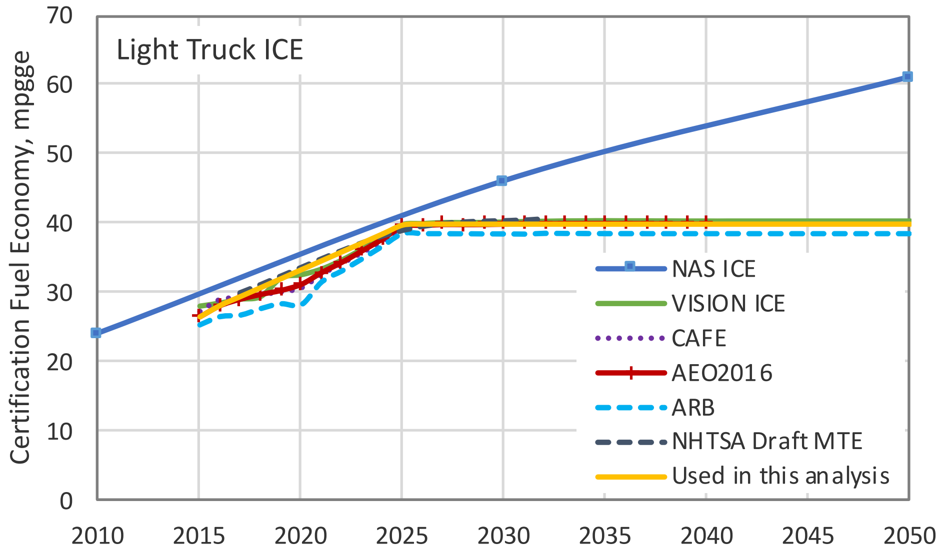

Figure A-23. Certification fuel economy forecasts for LDT gasoline ICEV

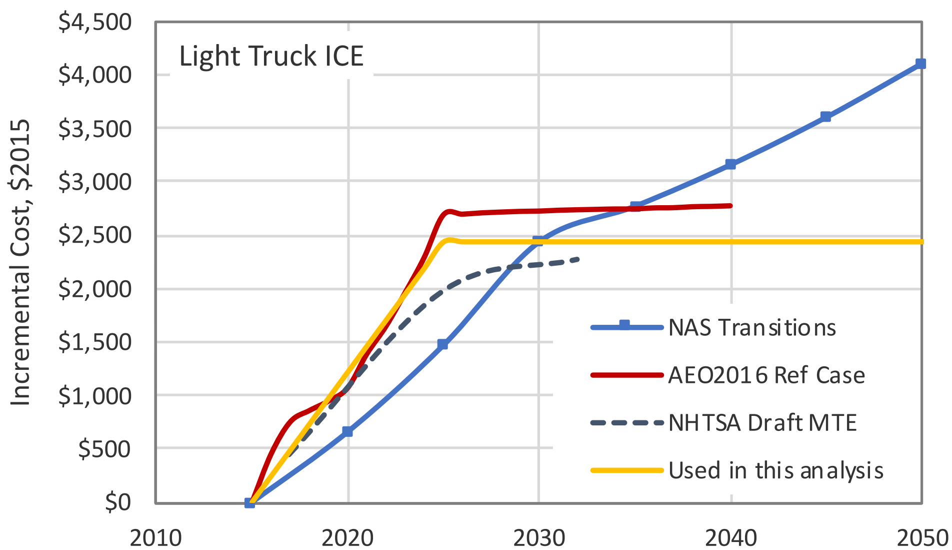

Figure A-24. Incremental cost forecasts for LDT gasoline ICEV

The forecasts for LT diesel fuel economy are illustrated in Figure A-25. For the U.S. analysis, the AEO2016 fuel economy values are used; for the CA analysis, the ARB forecast is used. The ARB and U.S. forecasts may be different due to different LDT1/LDT2/MDV market share assumptions. The AEO2016 forecasts for incremental cost are provided in Figure A-26. In the absence of any other incremental cost projections, the AEO2016 incremental cost is utilized.

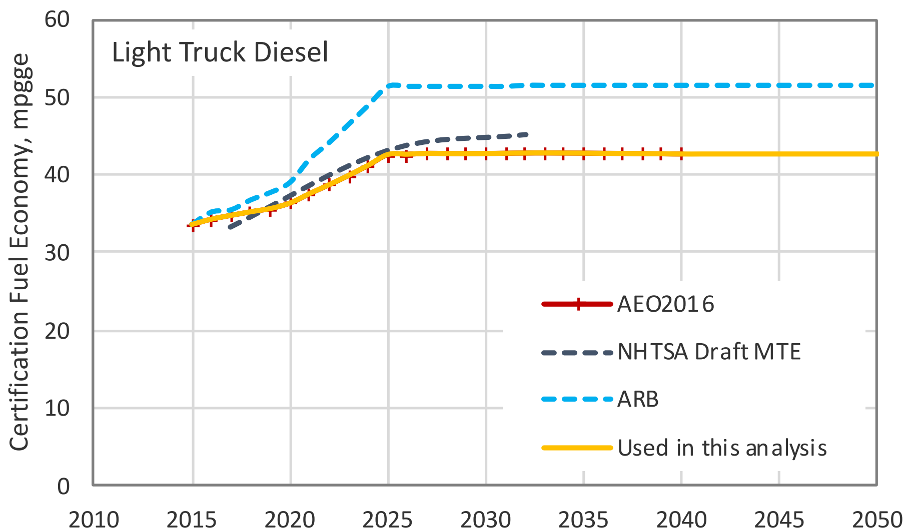

Figure A-25. Certification fuel economy forecasts for LDT diesel

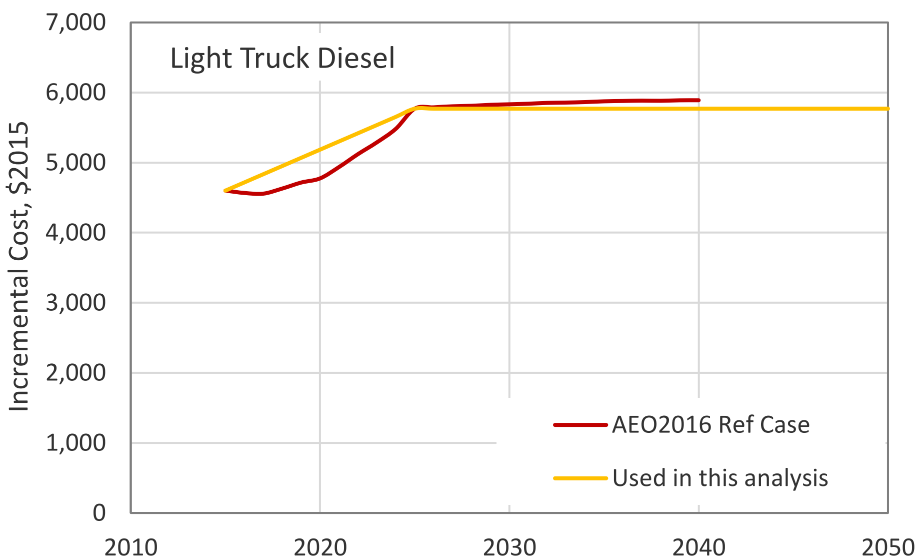

Figure A-26. Incremental cost forecasts for LDT diesel

There are 7 LDT hybrids on the market in 2016 (Figure A-27). The average EER is 1.26. Applying this EER to the gasoline ICE fuel economy, yields an average LDT HEV fuel economy of 35.4 mpg. The average incremental price is $7,100 for MY2016. The average without the luxury models is $4500, but more than half of the sales in 2015 were luxury models.

Figure A-28 summarizes the certification fuel economy forecasts. Most of the forecasts agree although the NHTSA Draft MTE values are difficult to understand with higher near-term fuel economy and lower or flat fuel economy in 2030. For this analysis, the current value (MY2016) is utilized for 2016, increasing linearly to the average of the AEO2016/NHTSA/NAS values in 2025.

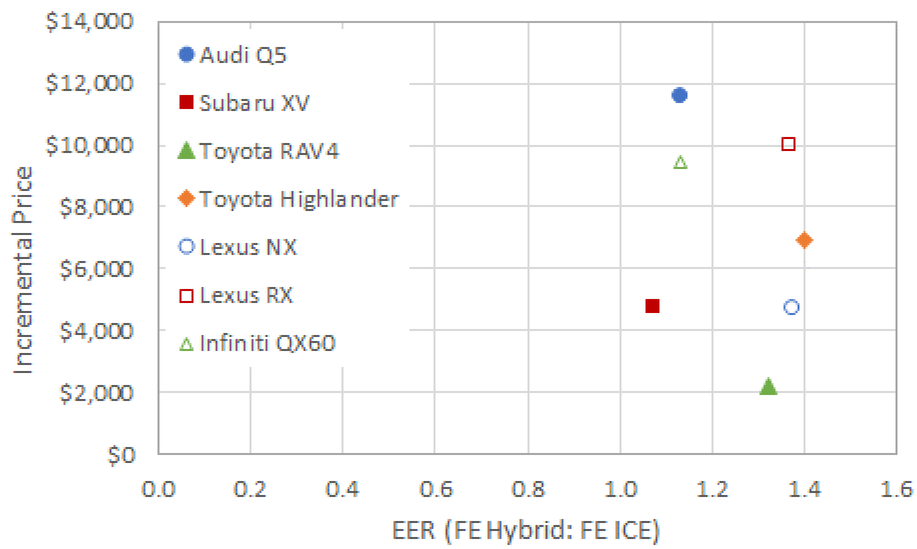

Figure A-27. Incremental cost vs. EER for MY2016 LDT HEV

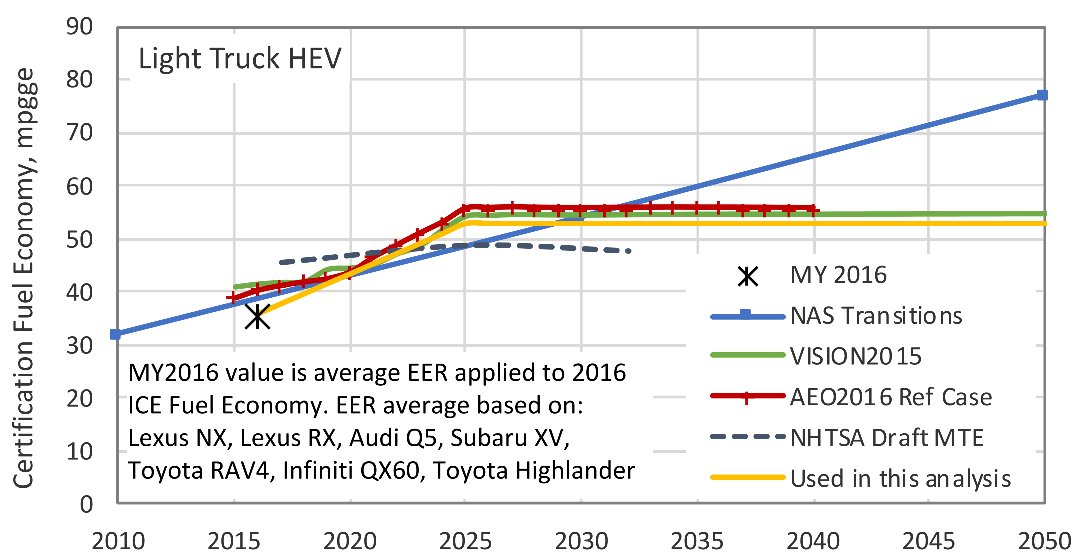

Figure A-28. Certification fuel economy forecasts for LDT HEV

Incremental cost forecasts are summarized in Figure A-29. The AEO2016 values are at the current average increment (with luxury models), but never decrease. The NHTSA and EPA Draft MTE forecasts are similar and seem to be more in line with the current average without the luxury models. For this analysis, the actual 2016 value (with luxury models) is used, decreasing to the EPA MTE value for 2025. The decline continues to slightly less than the 2030 NAS transitions value (which is actually higher than the NAS transitions value for 2025), remaining there through 2050. Although the assumed incremental cost for 2016-2018 may seem high, none of the analysis scenarios include increased sales of HEVs prior to 2018, so there is no impact on the analysis results.

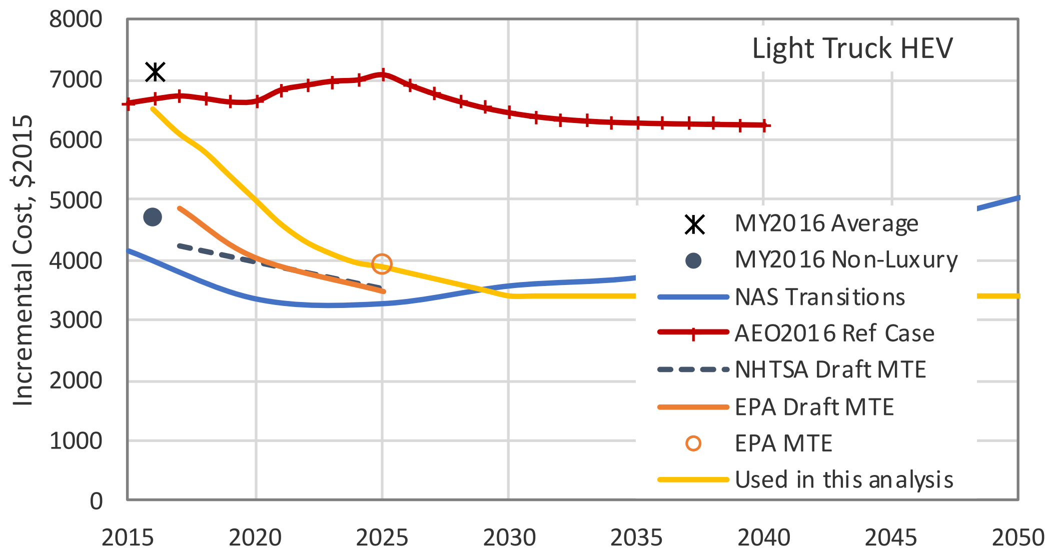

Figure A-29. Incremental cost forecasts for LDT HEV

The LDT BEV discussion starts with BEV200 because the only LDT BEV on the market is the Tesla Model X, which is a BEV200. Figure A-30 summarizes the LDT BEV200 certification fuel economy forecasts. The two Tesla models (different ranges) have similar fuel economy compared to the NHTSA and VISION2015 value for 2016. The NHTSA forecast is flat, in contrast to the AEO2016 value which increases rapidly to 200 mpgge in 2025. Strangely, the AEO2016 estimate for BEV200 is higher than their estimate for the BEV100 and also higher than their estimate for the light auto BEVs. For this analysis, we utilize the 2016 actual value and then increase along the NAS Transitions slope for the BEV100 (see Figure A-32).

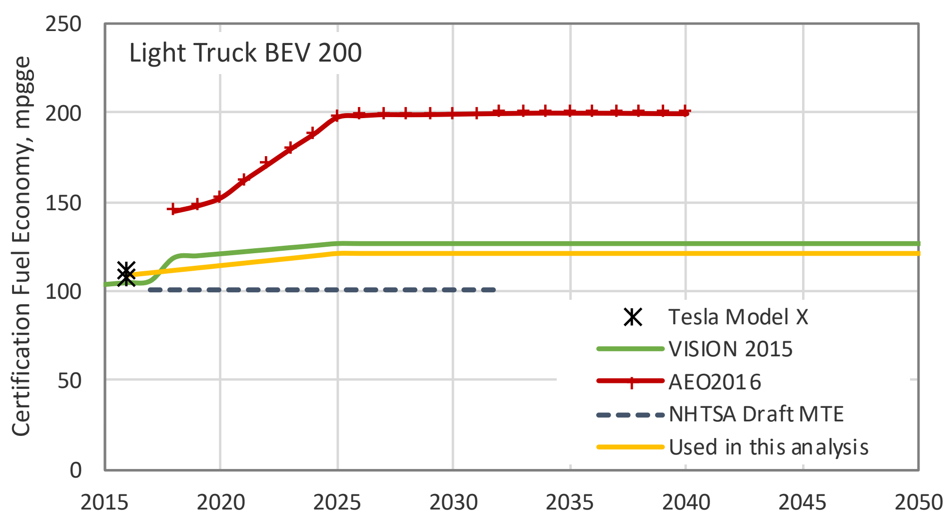

Figure A-30. Certification fuel economy forecasts for LDT BEV200

Incremental cost forecasts are shown in Figure A-31. Consistent with the light auto category, the NHTSA Draft MTE and AEO2016 forecasts are higher than the EPA Draft MTE forecast. The NAS Transitions forecast is mid-way between the two different MTE estimates. EPA's final MTE value is lower than its draft value. Recalling that the light auto EPA MTE values are more realistic than the NHTSA values, this analysis utilizes the midpoint between the NHTSA and EPA Draft MTE values for 2016, decreases to the 2025 EPA MTE value and settles slightly lower at $11,200 for 2030-2050.

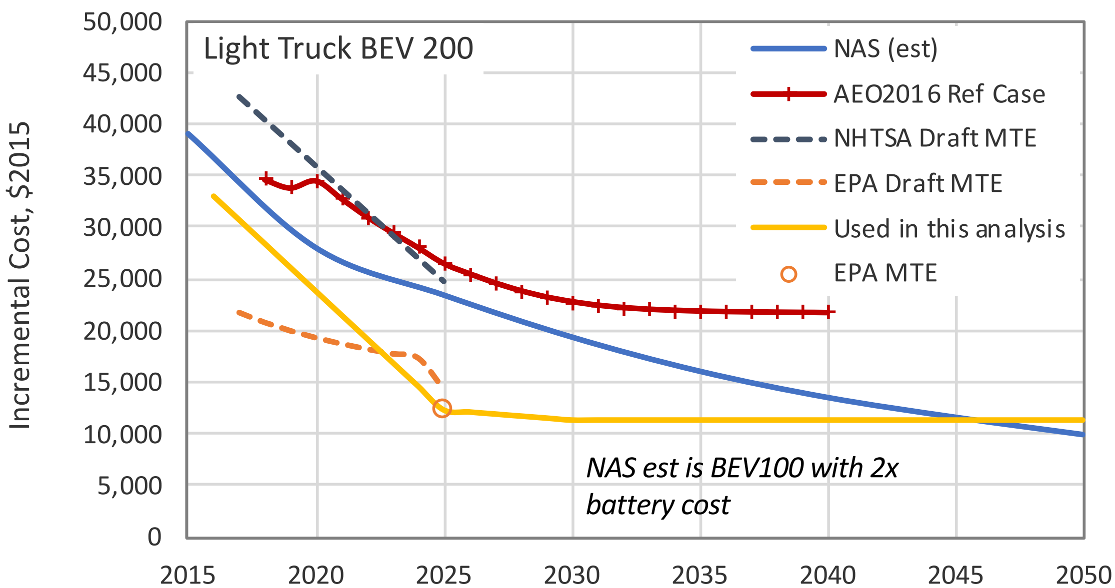

Figure A-31. Incremental cost forecasts for LDT BEV200

The BEV100 fuel economy forecasts are shown in Figure A-32. Note that there are no draft MTE fuel economy projections for LDT BEV100. The values used in this analysis are based on the BEV200 fuel economy projection (similar to the LDA BEV200 projection based on the BEV100). The BEV100 has 10% less weight than the BEV200 (assuming 233 Wh/kg, 45 kWh for the BEV100 and 95 kWh for the BEV200, and a 4600 lb vehicle), which corresponds to a 5.4% fuel economy benefit for the BEV100 relative to the BEV200. This correction applied to the BEV200 forecast lines up exactly with the NAS Transitions estimate.

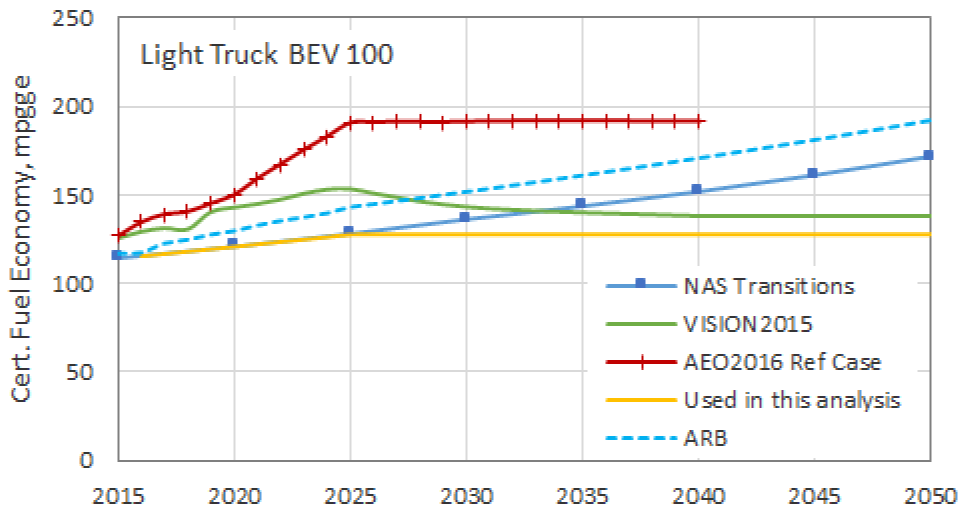

Figure A-32. Certification fuel economy forecasts for LDT BEV100

BEV100 incremental prices are shown in Figure A-33. Note that EPA's draft MTE forecast is similar to the NAS Transitions forecast and that EPA's final MTE value for 2025 is the same as its draft value. This analysis utilizes the EPA MTE and NAS Transition forecasts through 2025, leveling out at $9,000 for 2025-2050. Considerably higher than the NAS Transitions forecast in the out years. There is no NHTSA MTE estimate for BEV100 light trucks.

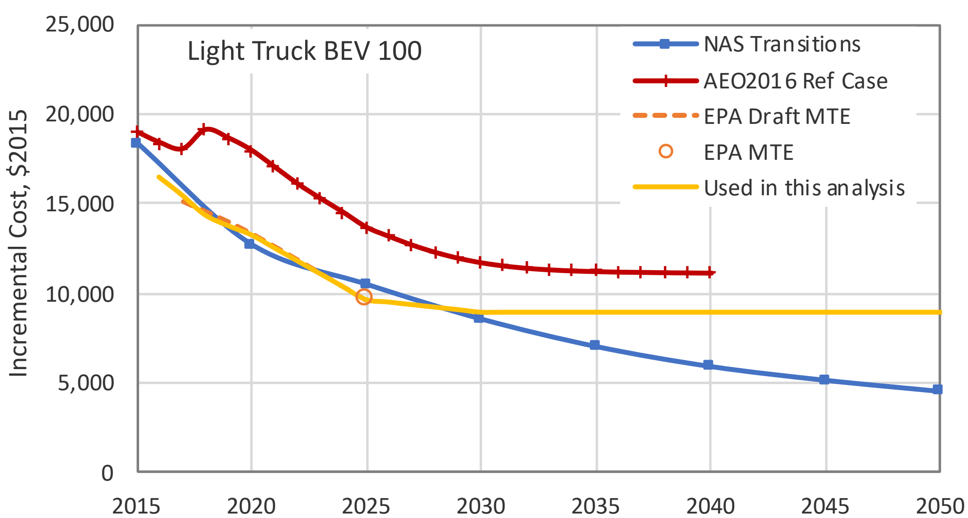

Figure A-33. Incremental cost forecasts for LDT BEV100

For MY2016, there are four LT PHEVs on the market with an average electric fuel economy of 50 mpgge sticker (~ 60 mpgge certification). Three of these models have ICE counterparts; their incremental price vs EER is shown in Figure A-34. The average EER is 2.5 and when this is applied to the ICE fuel economy, the result is 70 mpgge for electric mode. The average incremental price is $7,800 which is lower than the current LDA increment. Incremental price is difficult to discern in luxury vehicles.

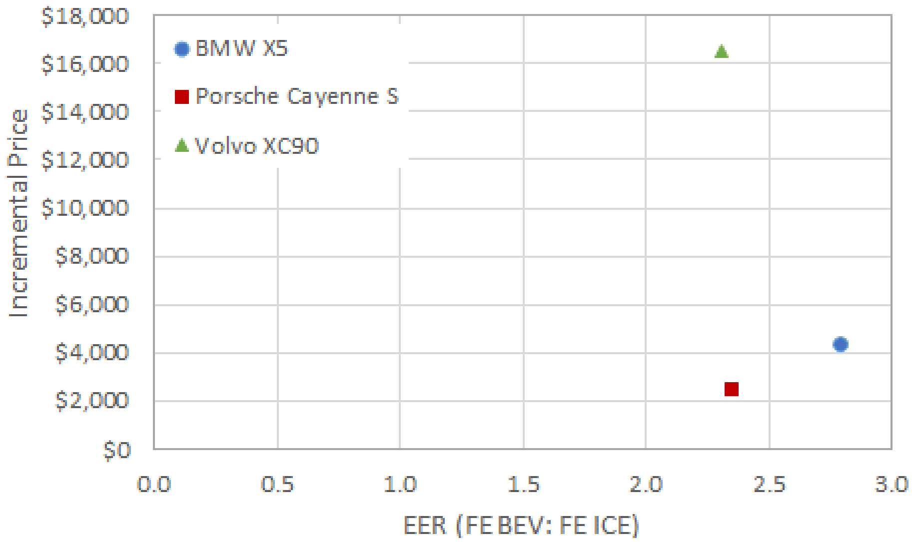

Figure A-34. Incremental cost vs electric mode EER for MY2016 LDT PHEV

Figure A-35 summarizes the electric mode fuel economy forecasts for light truck PHEVs. The NHTSA Draft MTE value is based only on the Porsche Cayenne. The NAS Transitions value is set equal to the BEV100 fuel economy (same as LDA). It is not clear why the current electric mode fuel economy in LDT PHEVs is so much lower than the BEV100 and BEV200 values. For this analysis, we start at the current value and increase linearly to the BEV100 estimate in 2025. Setting the electric mode fuel economy equal to the BEV100 values is consistent with the assumption for LDA that PHEV electric mode fuel economy is the same as the BEV100. It is also consistent with NAS Transitions and other studies.

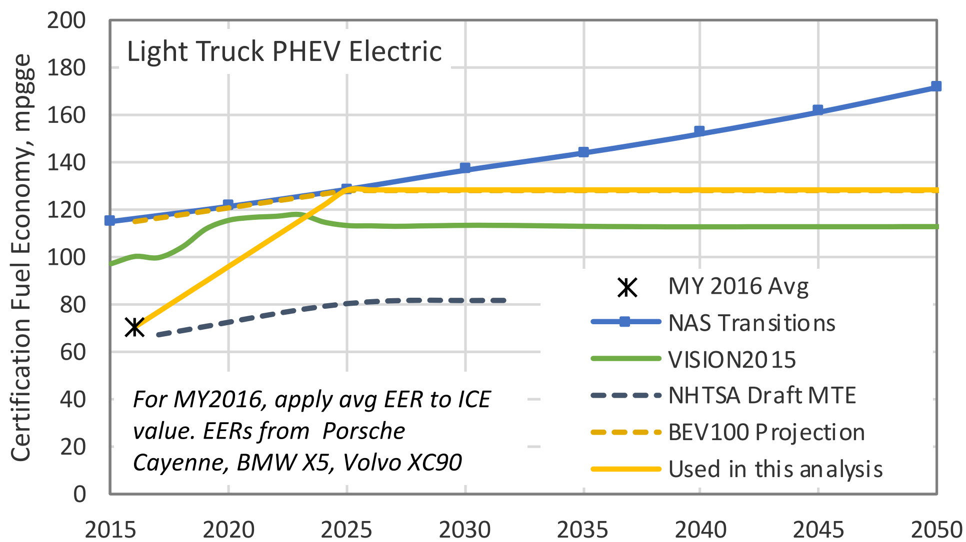

Figure A-35. Certification fuel economy forecasts for LDT PHEV

Incremental cost estimates are shown in Figure A-36. The AEO2016 and NHTSA Draft MTE estimates are on the high side while the NAS Transitions estimate is significantly lower. The EPA Draft MTE forecast is between these two estimates and lines up well with the current Volvo increment. Note that the MY2016 LDA PHEV increment is higher than the BMW and Porsche increments. This analysis utilizes the EPA Draft MTE values, leveling out at $12,000 in 2030.

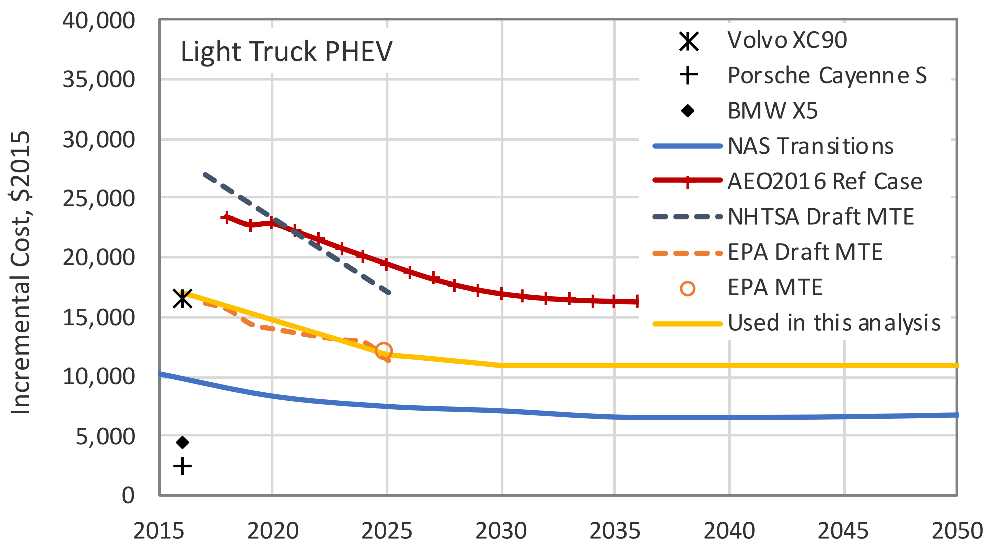

Figure A-36. Incremental cost forecasts for LDT PHEV

Figure A-37 presents the hydrogen FCV fuel economy forecasts. The MY2016 fuel cell Hyundai Tucson (small SUV) is close to the NAS Transitions estimate. The AEO2016 value is surprisingly low (same as gasoline ICE). For this analysis, fuel economy is set at the Tucson value, increasing linearly along the NAS slope until 2025 and leveling off there through 2050. Because our forecast is based on a small SUV, the projection could be biased on the high side. However, since our scenarios do not include increased penetration of FCVs during the analysis time frame, this bias does not affect the results.

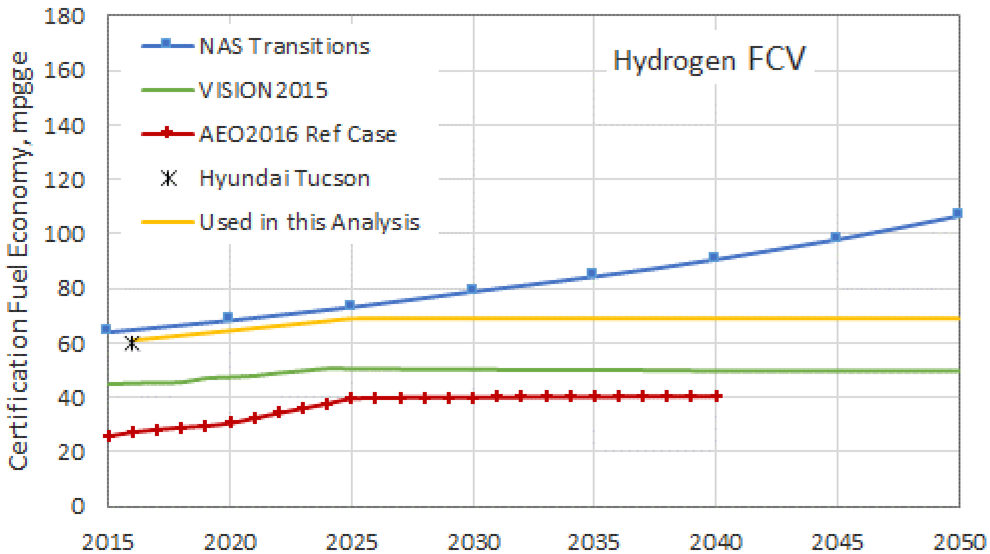

Figure A-37. Certification fuel economy forecasts for LDT H2 FCV

Incremental price estimates are provided in Figure A-38. Unfortunately, the Hyundai Tucson is only available for lease, so an actual incremental price is not available. The AEO2016 forecast is significantly higher than the NAS Transitions forecast, with the NHTSA Draft MTE forecast splitting the difference. Unfortunately, EPA did not provide an estimate for FCVs in the draft MTE. For this analysis, the NHTSA increment is utilized through 2025, decreasing linearly through 2040. Because this analysis does not consider scenarios with large market penetration of FCVs, it is assumed that economies of scale are achieved late in the analysis period.

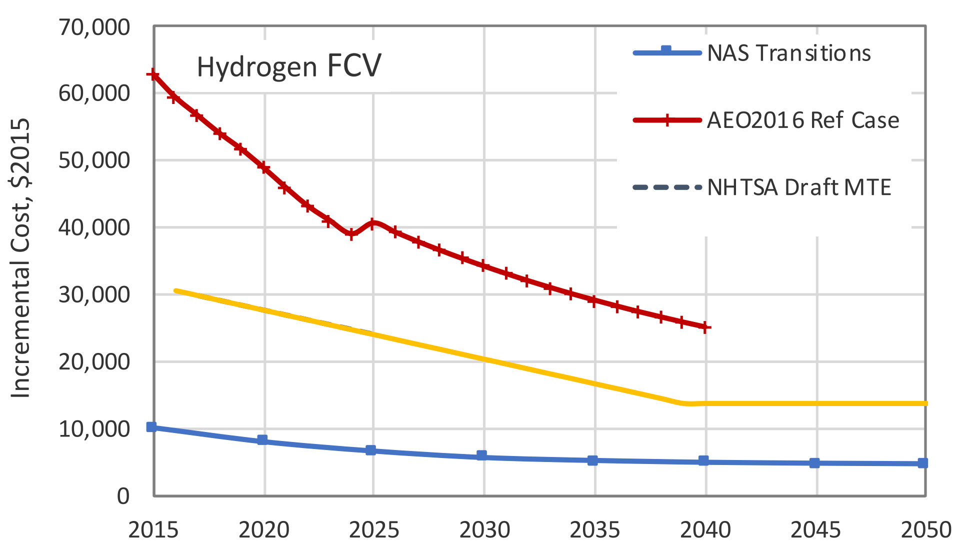

Figure A-38. Incremental cost forecasts for LDT H2 FCV

A summary of the light truck fuel economy and EER values used in the analysis are provided in Table A-5. The EER values are relative to the gasoline ICE in the year considered, for example, the 2025 EER value is the alternative fuel vehicle fuel economy in 2025 divided by the gasoline ICE fuel economy in 2025. Also provided is the annual average improvement for the 2016-2025 period and the 2025-2050 period. In contrast to the LDA fuel economy projections, the LDT electric drive fuel economy values do not improve significantly more on a mi/gal/year basis than the conventional vehicle fuel economy. One exception is the PHEV electric mode fuel economy – recall that the 2016 value is based on the three luxury models available today and then rapidly rises to the BEV100 fuel economy level by 2025. For this reason, the annual progress for 2016-2025 in mi/gal per year is much higher than the other technologies.

Table A-6 summarizes the values used in the analysis for incremental vehicle cost. The gasoline and diesel vehicles experience rising costs through 2025 while the other technology costs decrease dramatically. Note that the hydrogen FCV has much higher incremental cost through 2025 than the next most expensive technology (BEV200), with a significantly worse fuel economy.

Table A-5. Summary of LDT certification fuel economy and EER analysis values

	Certification FE, mpgge			EER			Progress, mi/gal/yr	
	2016	2025	2050	2016	2025	2050	2016-2025	2025-2050
Gasoline ICE	28	40	45	1.00	1.00	1.00	1.3	0.2
Diesel	34	42	48	1.21	1.07	1.07	0.9	0.2
FFV-Gasoline Mode	28	40	45	1.00	1.00	1.00	1.3	0.2
FFV-EtOH Mode	29	41	46	1.03	1.03	1.03	1.3	0.2
CNG	27	37	42	0.94	0.94	0.94	1.2	0.2
Gasoline HEV	36	53	64	1.28	1.33	1.41	1.9	0.4
PHEV-Gasoline Mode	36	53	64	1.28	1.33	1.41	1.9	0.4
PHEV-Electric Mode	70	128	175	2.48	3.22	3.88	6.4	1.9
BEV-100	115	128	175	4.08	3.22	3.88	1.4	1.9
BEV-200	109	121	166	3.87	3.06	3.68	1.4	1.8
Hydrogen FCV	61	69	94	2.16	1.74	2.10	0.9	1.0

Table A-6. Summary of LDT incremental costs (relative to 2015 gasoline ICEV)

	Incremental Cost, $2015			Annual Change, $/yr	
	2015	2025	2050	2016-2025	2025-2050
Gasoline ICE	0	2,438	2,438	244	0
Diesel	4,600	5,770	5,770	117	0
CNG	9,500	11,938	11,938	244	0
Gasoline HEV	6,500	3,884	3,400	-262	-19
PHEV	17,000	11,900	11,000	-510	-36
BEV-100	16,500	9,700	9,000	-680	-28
BEV-200	35,000	12,200	11,200	-2082	-39
Hydrogen FCV	30,744	24,050	13,638	-669	-417

Dedicated High Octane Fuel (HOF) Vehicles

Potential fuel economy gains due to higher octane gasoline is explored in this analysis. Higher octane fuels with a research octane number (RON) of 100 compared to the current 91 RON for regular grade gasoline would result in small but measurable fuel economy improvements in the legacy fleet and larger improvements in vehicles designed to operate on these fuels. Many vehicles in the existing fleet have knock sensors that retard the spark under high load (knock inducing) conditions, which degrades efficiency. With RON 100 fuels, existing engines would need less spark retard at load, resulting in improved efficiency and power output. Several recent studies[90,91] have been conducted that indicate legacy vehicles may experience a ~1.5% improvement in fuel economy with an increase in RON from current levels to 100. If the spark advance map in the engine software of these legacy vehicles were recalibrated, more improvement would likely be realized.

The primary reason dedicated HOF vehicles have improved fuel economy is because higher RON allows higher CR (without engine knock) which improves thermodynamic efficiency. Higher compression ratio in turn allows further engine downsizing for the same power output, resulting in additional fuel economy improvement. Aside from the compression ratio and downsizing effects, higher RON allows engines to run at lower speeds and consequently higher loads without engine knock, which improves efficiency. Finally, if the fuel's higher RON is achieved with ethanol blending, further improvement in efficiency could be achieved due ethanol's higher heat of vaporization. More energy is required to vaporize the fuel in the cylinder, lowering cylinder temperatures, reducing heat losses and pumping work.

A recent analysis attempts to correlate improvements resulting from increased RON and ethanol content for new dedicated vehicles[92]. The correlation assumes a one-unit increase in compression ratio for every 3 units of RON increase. Additionally, a 0.5% efficiency improvement is achieved for every 10% increase in ethanol content.

Table A-7 shows estimated efficiency improvement enabled by higher RON fuels. The estimated compression ratio for the E70 vehicle is extremely high – if a more modest estimate is used for new vehicle CR (13.2), the overall efficiency improvement is 7.7%. In addition, in this analysis, FFVs are assumed to have the same fuel economy as ICE vehicles while operating on gasoline, but while operating on E85, an EER of 1.03 was applied.

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[90] Effects of High Octane Ethanol Blends on Four Legacy FFVs and a Turbocharged GDI vehicle, John Thomas, Brian West, Shean Huff, March 2015, ORNL/TM-2015/116

[91] Ethanol and Air Quality: Influence of Fuel Ethanol Content on Emissions and Fuel Economy of FFVs, Carolyn Hubbard, James Anderson, Timothy Wallington, Ford Motor Company, ES&T 2014, 48, 861-867.

[92] The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on S-I Engine Efficiency, Thomas Leone, James Anderson, Michael Shelby, Ford Motor Company, Richard Davis and William Studzinski, General Motors Powertrain, Asim Iqbal, Ronald Reese, FCA USA LLC (Chrysler), ES&T 2015, 49 10778-10789.

Table A-7. Estimated HOF dedicated vehicle fuel economy improvement

Base Fuel	Base Vehicle CR	New Fuel	New Vehicle CR	Estimated Efficiency Improvement
E10, RON92	10.5	E10, RON100	13.2	4.5%
E10, RON92	10.5	E30, RON100	13.2	5.6%
E10, RON92	10.5	E70, RON103	16.4	8.8%
E10, RON92	10.5	E70, RON103	13.2	7.7%

Dedicated HOF vehicle incremental cost values are from the NAS Phase 2 report[93]. For high ethanol blend vehicles, costs are incurred for corrosion resistant injectors, with an estimated cost of $100 for a 6-cylinder auto. The incremental direct manufacturing cost of dedicated HOF vehicles is estimated to range from $75 to $150, depending on engine size. These manufacturing costs were marked up 30% for manufacturer markup and an additional 16% for the dealer markup. The resulting incremental cost projections are shown in Figure A-39 and Figure A-40.

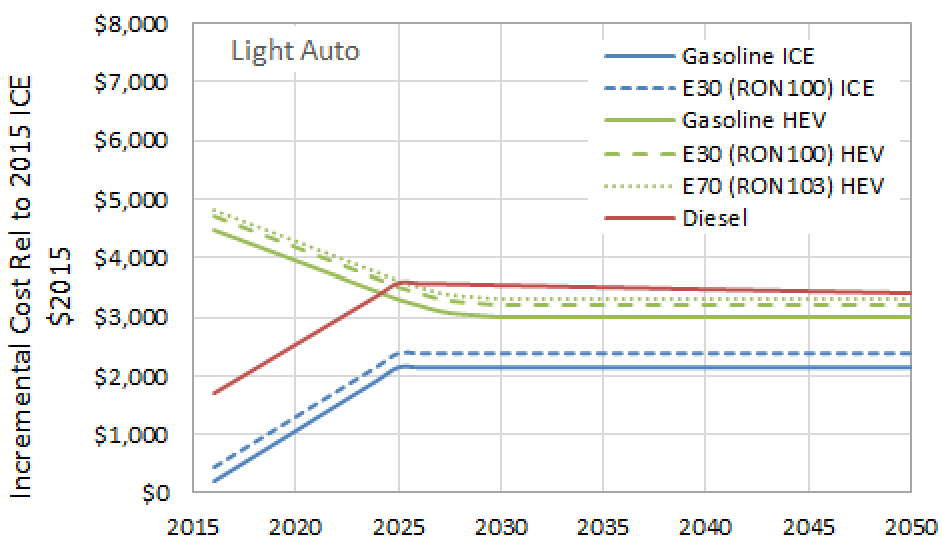

Figure A-39. Incremental cost of dedicated HOF light autos

[93] *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-duty Vehicles*, National Academy of Sciences, 2015.

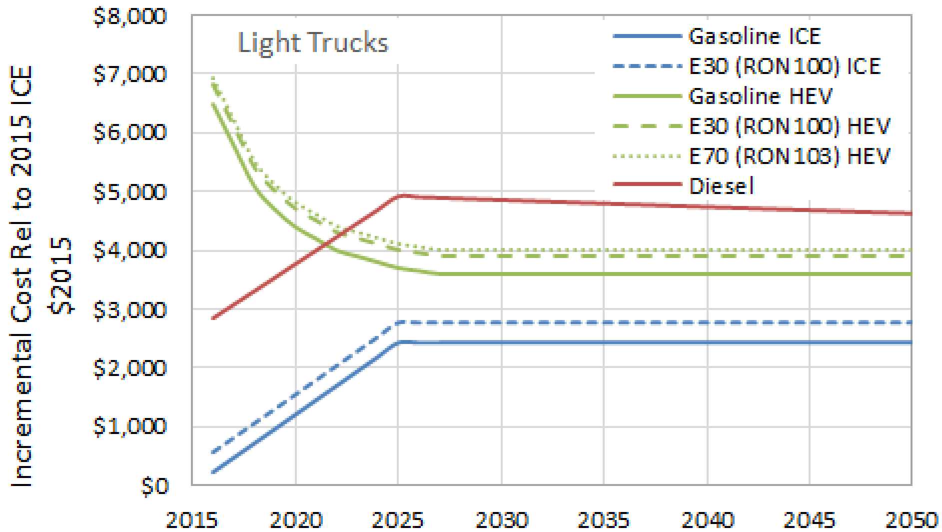

Figure A-40. Incremental cost of HOF light trucks

Appendix B Carbon Intensity Estimates for U.S. Analysis

To quantify GHG emissions in this analysis, carbon intensity (CI) values for each fuel type were selected. CI is defined here as the mass of GHG emissions per unit energy of fuel. The GHG pollutants included are CO_2, CH_4, and N_2O[94] and emissions are quantified on a "well-to-wheel" basis which includes emissions from fuel production activities and vehicle emissions. Two sets of CI values were developed – one for California and one for the entire U.S. Because the analysis extends to 2050, changes in CI over time are quantified. Key considerations for the time dependent estimates are crude oil origin and type, natural gas sources and leakage rates, and electricity generation resource mix. Table B-1 shows the fuel pathways for which CI values were developed.

Table B-1. Fuel and feedstock combinations for which CI values are quantified

Finished Fuels	Feedstocks
Gasoline Blendstock for E10 Gasoline Blendstock for E10 RON100 Gasoline Blendstock for HOF E30 Natural Gasoline (E85 Blendstock)	Petroleum Crude and Cellulose Petroleum Crude Petroleum Crude Natural Gas Recovery
Ultra Low Sulfur Diesel	Petroleum Crude and Cellulose
Ethanol (neat)	Corn, Brazilian Sugarcane, Cellulose, NG
Biodiesel	Soybeans, Canola, Corn, Waste Oil
CNG	Natural Gas, Renewable Natural Gas
Electricity	Grid Average
Hydrogen	Natural gas on-site reforming

The GREET[95] model was utilized to quantify CI values. In brief, for each step in a fuel's life cycle, the GREET model methodically calculates direct and upstream GHG and criteria pollutant emissions. The emissions for each step are calculated based on an assumed process efficiency that dictates the total amount of fuel consumed per unit of product produced. The total fuel consumption is split among different fuel types (e.g. crude oil, residual oil, gasoline, natural gas, electricity, etc.). For each fuel type, the portion consumed in each different type of combustion equipment is also assumed. Non-combustion emissions such as venting are also included. With these assumptions (process efficiency, fuel shares, combustion device shares, other process emissions), the total direct emissions can be calculated.

[94] GHGs = $CO_2 + GWP_{CH4}*CH_4 + GWP_{N2O}*N_2O$ where the GWP values are Global Warming Potential factors. GWP factors from the IPCC Fifth Assessment Report were used: 30 for CH_4 and 260 for N_2O. This set of factors is the default selection in GREET1_2015.

[95] Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model, Argonne National Laboratory. GREET1_2015 released Oct 2, 2015.

Upstream emissions are emissions produced in production and transport of the process fuels that are directly consumed. For example, a process might specify that an amount of natural gas is combusted in a boiler. The direct emissions of natural gas combustion in a boiler are quantified, and the upstream emissions associated with natural gas recovery, processing, transmission and distribution are added. Inclusion of the upstream emissions renders the calculations iterative and changes to one fuel pathway affect all pathways that utilize that fuel. For example, changes in assumptions about natural gas recovery affect not only the CI of the natural gas-based fuels, but also the CI values for all fuels that utilize natural gas as a process fuel in their production.

Carbon intensity values utilized in the U.S. analysis were estimated with the most recent version of the GREET model, GREET1_2015. Recently the GREET1_2016 version was released. Key differences between the version adapted for this analysis and the newly released version are noted. In many cases the model was updated with the new assumptions in GREET1_2016. CI values for 2016, 2020 and 2040 were calculated with the GREET1_2015 version of the model updated by LCA. CI values are assumed to change linearly for the periods 2016 to 2020 and 2020 to 2040; 2050 values are assumed to be equal to 2040 values. The following sections describe the underlying assumptions for the fuel pathways in Table B-1. A summary of the resulting CI values is provided at the end of this section.

Petroleum Fuel Assumptions

Petroleum fuel well-to-tank (WTT) CI values can be divided into the crude oil portion and the refining portion. The crude oil portion is the same for gasoline blendstock and diesel. The GREET model calculates crude oil recovery and transport emissions by assuming a crude slate based on EIA[96] projections. Table B-2 provides the GREET1_2015 and GREET1_2016 assumptions on crude origin. The GREET1_2016 values are taken from AEO2015 projections. Because 2020 is the last year in the GREET time series, the AEO2015 value for domestic crude share was used here. Note that EIA's NEMS model predicts a decrease in domestic production. The GREET default shares for the other crude sources were renormalized as shown. The GREET model utilized for this analysis has been updated with the GREET1_2016 values for crude origin.

Table B-2. Crude oil source time series (vol%)

Crude Source	GREET1_2015		GREET1_2016		EIA[97]	Analysis Values		
	2016	2020	2016	2020	2040	2016	2020	2040
US Domestic	54.3%	65.8%	56.7%	61.9%	51.7%	56.7%	61.9%	51.7%
Canadian Oil Sands	9.8%	12.0%	10.3%	12.9%		10.3%	12.9%	14.7%
Canadian Conv	8.4%	7.0%	9.2%	7.5%		9.2%	7.5%	8.5%
Mexico	4.6%	2.5%	3.4%	3.1%		3.4%	3.1%	3.6%
Middle East	11.5%	6.3%	8.9%	8.1%		8.9%	8.1%	9.2%
Latin America	8.9%	4.9%	9.5%	8.7%		9.5%	8.7%	9.8%
Africa	1.9%	1.0%	1.7%	1.6%		1.7%	1.6%	1.8%
Other	0.6%	0.3%	0.7%	0.7%		0.7%	0.7%	0.8%

[96] DOE's Energy Information Administration

[97] AEO2015 Reference Case, Petroleum Supply and Disposition.

Table B-3 provides the GREET default time series for U.S. crude oil by type. These values have not been updated in GREET1_2016. Default crude oil transport modes and distances based on crude slate were utilized.

Table B-3. GREET default time series for US domestic crude sources (vol%)

	Bakken Shale	Eagle Ford Shale	Other U.S. Domestic
2016	14.3%	17.6%	68.2%
2020	14.7%	18.1%	67.2%
2030	13.4%	16.5%	70.2%

The GREET model quantifies CI for three gasoline blendstocks:

- Blendstock for gasoline with denatured ethanol content of 10% by volume (E10)
- Blendstock for high octane fuel with 30% denatured ethanol content (HOF E25)
- Blendstock for high octane fuel with 70% denatured ethanol content (HOF E40)

For E10, the model calculates refining efficiency based on crude slate API, sulfur content, refinery heavy product yield, and Nelson complexity index[98]. Because the slate changes over time, the gasoline and diesel refining efficiencies vary over time as shown in Table B-4. The table also provides the refining efficiencies for the two HOF blendstocks. GREET1_2016 provides refining efficiency for each of the PADDs; the values shown in the table and utilized in the analysis are an average of the PADD values. The linear programming analysis used to estimate the HOF refining efficiency values is documented in a recent ANL publication.[99] For this analysis, we will utilize one HOF fuel with 30% ethanol content (HOF E30), which was determined by scaling the GREET HOF E25 and HOF E40 results.

Table B-4. Petroleum fuel refining efficiencies

Fuel	2016	2020	2040
E10 Blendstock	88.6%	88.6%	88.4%
HOF E25 Blendstock		89.0%	
HOF E40 Blendstock		87.8%	
Ultra Low Sulfur Diesel	90.9%	90.9%	90.7%

A relatively new addition to the GREET model is a factor called "Energy Ratio of Crude Oil Feed to Product". This factor allocates the amount of crude recovery and transport emissions to the different refinery products and is based on refinery modeling performed by Argonne National

[98] *Analysis of Petroleum Refining Energy Efficiency of U.S. Refineries*, Argonne National Lab (Cai, Han, Forman, Divita, Elgowainy, Wang), Sasol, and Jacobs Consultancy, 2013.
[99] *Well-to-Wheels Greenhouse Gas Emissions Analysis of High Octane Fuels with Various Market Shares and Ethanol Blending Levels*, Argonne National Lab (Han, Elgowainy, Wang) and Jacobs Consultancy, July 2015.

Laboratory[100]. The units are MJ of crude oil per MJ of product. Previous versions of the model assumed a ratio of 1.0 for all refinery products. Table B-5 provides the GREET1_2016 values for this energy ratio. The E10 and diesel ratios are unchanged from the previous GREET version, but the HOF ratios are much lower compared to the previous values. Lower ratios of crude to product result in lower CI values. Natural gasoline is the assumed blendstock for higher level ethanol blends (E85) in FFVs because this is typically used at present. However, the supply of natural gasoline may be limited, so the scenarios with high penetration rates of E85 HEVs and E85 PHEVs employ gasoline blendstock rather than natural gasoline. Carbon intensity assumptions for natural gasoline blendstock is described several sections below.

Table B-5. Ratio of crude use per unit feedstock

Fuel	MJ Crude per MJ product
E10 Blendstock	0.863
HOF E25 Blendstock	0.916
HOF E40 Blendstock	0.920
Ultra Low Sulfur Diesel	1.001

Natural Gas Production Inputs

This section provides the key assumptions in the natural gas production, distribution and transmission emissions. Table B-6 provides the GREET default values for domestic natural gas recovery efficiency, processing efficiency, and the share of the domestic supply that is produced from shale. These values have not been updated in GREET1_2016. We assume in this analysis that all the natural gas consumed is domestic.

Table B-6. GREET default values for NG recovery and processing

	Portion of NG Supply from Shale	Recovery Efficiency		Processing Efficiency
		Conventional	Shale	
2016	51.5%	97.5%	97.6%	97.4%
2020	53.6%			
2040	55.2%			

One significant issue for natural gas is the quantity of methane that leaks and is vented during recovery, processing, transmission, and distribution. For the most recent version of GREET, ANL updated the leak rates to be consistent with the 2015 EPA GHG inventory (based on 2013 data)[101]. The Environmental Defense Fund (EDF) has recently commissioned a suite of studies to

[100] *Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries*, Argonne National Lab (Elgowainy, Han, Cai, Wang) Sasol (Forman), and Jacobs Consultancy (DiVita), May 2014.
[101] *Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET1_2015 model*, ANL (Burnham, Elgowainy, Wang), October 2015.

try to better quantify the natural gas industry methane emissions. Table 5 of the ANL study provides a comparison of the EPA Greenhouse Gas Inventory (GHGI) values and those from the EDF studies. The EDF sponsored reports include one for gas field emissions by Allen[102], another for gathering and processing emissions by Marchese[103], a report by Zimmerle[104] on methane emissions in transmission, and another by Lamb[105] on distribution emissions. To compare the emission estimates, ANL divided the emission estimates in these reports by EIA estimated total withdrawals to arrive at an emission rate normalized to gas throughput.

Table B-7 provides the values from ANL's table along with those from Tong[106] and the EPA GHGI; default values in GREET1_2015 and GREET1_2016 are also shown. The EPA GHGI gas field emission estimate is like the value estimated by Allen, but lower than those estimated by both by EDF studies (Marchese and Tong). Note that the GREET1_2015 estimates for processing, transmission and distribution in GREET are higher than the EDF study values and similar to those estimated by Tong. The GREET1_2016 values are markedly different from the prior model version. Gas field emissions have more than doubled while distribution emissions have decreased. Total leakage has increased and appears to be higher than the other estimates shown. For this analysis, updated GREET1_2016 values were used.

Table B-7. Summary of recent upstream natural gas methane leakage estimates

Activity	GREET1_2015		GREET1_2016		EPA GHGI, 2015	Allen, 2013*	EDF Studies 2015*	Tong, 2015**
	Shale	Conv	Shale	Conv				
Gas Field	0.34%	0.30%	0.77%	0.70%	0.31%	0.38%	0.58%	0.49%
Processing	0.13%		0.13%		0.15%	n/a	0.09%	0.04%
Transmission	0.41%		0.36%		0.36%	n/a	0.25%	0.46%
Distribution	0.33%		0.09%		0.22%	n/a	0.07%	0.31%
Total	1.18%	1.22%	1.28%	1.34%	1.04%		0.99%	1.30%

*Taken from ANL report Table 5 – ANL divided reported methane emission values by EIA gross withdrawals. The Gas Field value utilizes EPA's value for gas field emissions (0.31%) and Marchese's value for gathering (0.27%). The processing value is a combination of EPA's value for routine maintenance and Marchese's processing value.

** Gas field estimate also includes road construction, well drilling, and fracking emissions

[102] *Measurements of methane emissions at natural gas production sites in the United States*, David Allen et al, 2013 sponsored by Environmental Defense Fund.

[103] *Methane Emissions from United States Natural Gas Gathering and Processing*, Marchese et al, 2015

[104] *Methane Emissions from the Natural Gas Transmission and Storage System in the United States*, Daniel Zimmerle et al, July 2015

[105] *Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States*, Brian Lamb et al, March 2015

[106] A Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Medium- and Heavy-duty Vehicles, Fan Tong et al, 2015

GREET maintains constant methane leakage rates over time. In August of 2015, EPA proposed New Source Performance Standards (NSPS) for new and modified equipment in the oil and gas sector. EPA estimates that if the proposed rule is adopted, methane emissions from oil and gas production will decrease by 170,000 short tons in 2020 and 340,000 short tons in 2025. A rough allocation of these emissions reductions between oil and gas production results in approximately 9 percent reduction in gas field methane emissions and a 4% reduction in processing emissions in 2025 with negligible reductions in T&D emissions.

President Obama and Canadian Prime Minister Trudeau pledged to reduce methane emissions from the oil and gas industry by 40% from 2012 levels over the next decade. President Obama's EPA administrator, Gina McCarthy has stated that to meet this goal, new regulations targeting existing sources will need to be promulgated. Because the NSPS standards for new sources and regulations targeting existing source have not been finalized and because the new President opposes environmental regulation, these reductions are not included in this analysis. These controls would reduce the gasoline CI by 0.3% and the CNG CI by 4% in 2040. The vehicle emissions are a large part of the CI for these fuel pathways.

Natural Gasoline Assumptions

Natural gasoline is collected as a condensate at oil and natural gas wells and is currently used as a blending agent for high ethanol blends (E70-E85) (ASTM D5798-13a) for FFVs. Natural gasoline is composed mainly of pentanes with some butanes and hexanes. Natural gasoline is separated from natural gas at the NG recovery processing facility via condensation or distillation. Although the GREET model does not explicitly model natural gasoline, the natural gasoline pathway CI can be estimated using the NG recovery and processing components in GREET combined with the default fuel transport assumptions (mode share and miles) of methanol (correcting for the heating value and density of natural gasoline compared to conventional gasoline[107]). The resulting CI for natural gasoline is 92.1 gCO2e/MJ in 2020.

Electricity Inputs

One key input for the CI calculation of most fuels is the resource mix that is utilized to generate electricity. Table B-8 shows the AEO2016[108] reference case projection. The reference case assumes implementation of EPA's Clean Power Plan (CPP) which was finalized but stayed by the U.S. Supreme Court in February of 2016 while the U.S. Court of Appeals for the District of Columbia reviews it. The lower court will make its ruling in early 2017 and it appeared in September 2016 that the CPP would go forward albeit with a late start.[109] However, on the campaign trail, the new President vowed to undo the CPP and every indication early in his

[107] A ratio of motor gasoline blend component to natural gasoline of 0.885, taken from EIA's Monthly Energy Review - Section 13, is utilized to estimate natural gasoline lower heating value.
[108] U.S. Energy Information Administration Annual Energy Outlook (AEO2016).
[109] "EPA's Clean Power Plan Does Well in Court: Both sides in the fierce legal battle acknowledge that EPA has the early edge", Emily Holden, September 2016, Scientific American. https://www.scientificamerican.com/article/epa-s-clean-power-plan-does-well-in-court/

presidency indicates that CPP will likely not be implemented. There is an AEO2016 side case without the CPP. Both electricity grid mix forecasts are shown in Table B-8. Without the CPP, the coal share in 2040 is projected to be 50% higher than it would be with the CPP.

Three different electricity grid mixes are utilized in this analysis: AEO2016 reference case, AEO2016 reference case without CPP, and low-CI mix with 70% non-fossil generation by 2040. Table B-9 provides the 70% non-fossil mix over time. Figure B-1 illustrates the 2040 resource mix for each case considered here. Note that changing electricity grid mix affects all fuel pathways that utilize electricity in their production.

Table B-8. Projections of U.S. average electricity generation resource mix

	AEO2016 Reference					AEO2016 Reference w/o CPP				
	Oil	NG	Coal	Nuclear	Renew -able	Oil	NG	Coal	Nuclear	Renew -able
2015	1%	26%	37%	22%	14%	1%	26%	37%	22%	14%
2020	0%	22%	37%	21%	20%	0%	22%	38%	21%	19%
2025	0%	24%	31%	21%	23%	0%	23%	37%	20%	20%
2030	0%	29%	25%	21%	25%	0%	24%	35%	20%	20%
2035	0%	28%	24%	20%	27%	0%	25%	34%	19%	22%
2040	0%	29%	22%	20%	28%	0%	26%	32%	19%	23%

Table B-9. Projections of U.S. average electricity generation resource mix

	70% Non-Fossil Grid Mix				
	Oil	NG	Coal	Nuclear	Renew
2015	0.7%	26%	37%	22%	14%
2020	0.4%	22%	30%	21%	27%
2025	0.3%	24%	23%	21%	32%
2030	0.3%	29%	15%	21%	35%
2035	0.2%	28%	8%	20%	43%
2040	0.1%	30%	0%	20%	50%

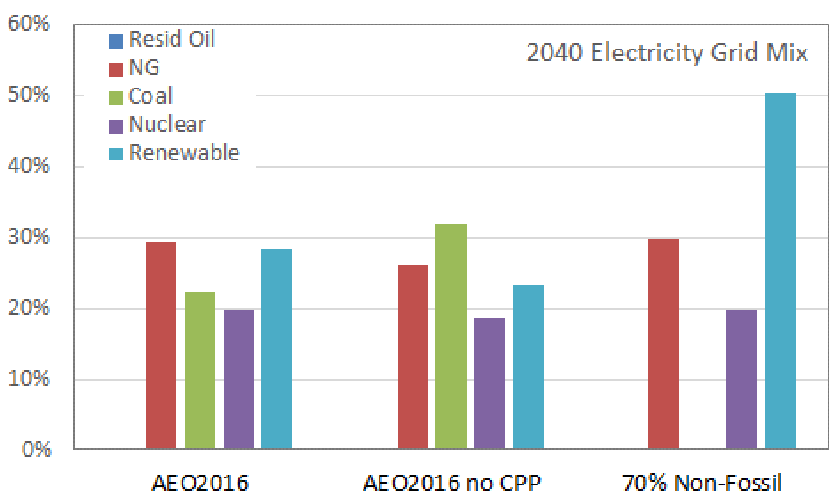

Figure B-1. Comparison of three analysis grid mixes

GREET also assumes that 3% of coal fired generating capacity would be integrated gasification combined cycle (IGCC) by 2020. According to EIA, total coal generating capacity decreased from 318 GW in 2011 to 281 GW in 2015[110]. If the aging coal fleet continues to retire in the face of inexpensive natural gas at the same rate, coal capacity in 2020 will be 235 GW. A review of the EPA Clean Air Markets Database indicates that Polk, the first coal fired IGCC unit is currently not operating. Wabash is operating but not on coal. The only IGCC plant currently operating on coal is Edwardsport with a total capacity of 618 MW. Currently two IGCC plants are nearing commercial operation: Kemper City Ratcliffe plant (operating on pipeline NG in 2015) and the Texas Clean Energy project. If all four plants were operational in 2020, they would represent approximately 0.7% of total projected coal capacity. For this analysis, the GREET default of 3% IGCC was reduced to 0.7%.

Corn Ethanol Assumptions

For the analysis, a U.S. average corn ethanol CI value is utilized. Corn ethanol CI consists of farming emissions, corn transport emissions, ethanol production emissions, credits for co-products displacing other products, and ethanol transport. Table B-10 provides the GREET default farming energy use and chemical use. All inputs are assumed to decline to 2020. For this study, the 2040 farming inputs are assumed to be the same as 2020 inputs.

GREET calculates CI values for three types of corn ethanol plants: dry mill plants, dry mill plants that co-produce corn oil, and wet mill plants. Each type has different ethanol yields, fuel consumption, and byproduct yields. Table B-11 summarizes the default yield values in GREET along with total process fuel use estimates. This analysis utilizes the GREET values. Ethanol yield values in 2040 are assumed to be the same as the yield in 2020.

Table B-10. Projected corn farming inputs

GREET Default Values	Units	2015	2020
Farming Energy Use	Btu/bu	9,142	8,698
Nitrogen Use	gN/bu	403	383
Phosphorus Use	g P_2O_5/bu	139	132
Potassium Use	g K_2O /bu	144	137
Calcium Use	g $CaCO_3$ /bu	1,094	1,041
Insecticide Use	g/bu	0.06	0.06
Herbicide Use	g/bu	7	7

Table B-11. GREET default ethanol plant yields and energy use

	Ethanol Yield, gal/bu		Dry DGS	CGF	CGM	Oil	Fuel Use
	2015	2020	lb/gal	lb/gal	lb/gal	lb/gal	Btu/gal
Dry Mill no Oil Extraction	2.86	2.93	5.63				26,856
Dry Mill – with Oil Extraction	2.88	2.95	5.39			0.19	26,421
Wet Mill	2.67	2.74		5.28	1.22	0.98	47,409

[110] EIA Table 4-3 "Existing Capacity by Energy Source" and Form EIA-860.

The distribution of plants between wet and dry mill are summarized in Table B-12. GREET projects a drop in older less efficient wet mill plants from 2015 to 2020. This study assumes that the trend continues such that by 2040, only 5% of plants are wet mill. GREET assumes an 80/20 split of dry mill plants between those that co-produce corn oil and those that don't. GREET also assumes that the share of process fuel that is coal is 8% for dry mill plants and 27.5% for wet mill plants. This study assumes that by 2040, coal use decreases to 2% for dry mill plants and 15% for wet mill plants.

Table B-12. Corn ethanol plant types and fuel share projections

	Plant Shares			% Coal as Process Fuel		
	2015	2020	2040*	2015	2020	2040*
Dry Mill no Oil Extraction	17.7%	18.2%	19%	8%	8%	2%
Dry Mill – with Oil Extraction	70.9%	72.9%	76%	8%	8%	2%
Wet Mill	11.4%	8.9%	5%	27.5%	27.5%	15%

* No GREET default value for 2040. Estimate for this study.

Sugarcane Ethanol Assumptions

For the analysis, an average Brazil sugarcane CI value is utilized. Sugarcane ethanol CI consists of emissions from farming, field burning, sugarcane transport, ethanol production emissions, a credit for exported electricity and ethanol transport. GREET defaults for sugarcane farming inputs are shown in Table B-13. These values are utilized in the present analysis for all analysis years. Table B-14 provides assumptions regarding sugarcane harvesting. It is assumed that by 2020, the practice of field burning will be eliminated, and the share of sugarcane left in fields with mechanized harvesting will decrease from 64% to 60% by 2020. For this analysis, the default values for field burning were used; additionally, the share of cane left in unburned fields is assumed to remain constant from 2020 to 2050.

Table B-13. GREET1_2015 default sugarcane farming inputs

GREET Default Values	Units	2015-2040
Farming Energy Use	Btu/wet tonne	95,000
Nitrogen Use	g N/wet tonne	800
Phosphorus Use	g P_2O_5/wet tonne	300
Potassium Use	g K_2O /wet tonne	1,000
Calcium Use	g $CaCO_3$ /wet tonne	5,200
Insecticide Use	g/wet tonne	45
Herbicide Use	g/wet tonne	2.5

Table B-14. Assumptions regarding sugarcane harvesting

GREET Default Values	2015	2020
Share of fields with manual cutting	15%	0%
Share of fields with field burning	15%	0%
Share of cane left in unburned fields	64%	60%

Sugarcane ethanol plants utilize bagasse to generate steam and electricity to run the plant. Excess electricity is exported to the grid; we assume a credit for this electricity equivalent to the average Brazil electricity resource mix. Table B-15 provides ethanol plant operating assumptions. The GREET default electricity export quantities might be considered aggressive, especially since they are an average value for all sugarcane ethanol plants in Brazil. The Table provides slightly lower values utilized in this study.

Table B-15. Ethanol plant operating assumptions

Values	Units	2015	2020	2040
Ethanol Yield	gal/wet tonne	21.4	21.4	21.4
Energy Use	Btu/gal	300	300	300
Exported Electricity (GREET)	kWh/gal	3.5	4.7	4.7
Exported Electricity (this analysis)	kWh/gal	3	4	4

Cellulosic Ethanol Inputs

The federal Renewable Fuel Standard (RFS2)[111] requires an increasing portion of ethanol sales to be produced from cellulosic feedstocks. Several fuel feedstocks are potential options for cellulosic ethanol. These include corn stover and other crop residues, energy crops such as switch grass, forest residues, municipal solid waste, and other cellulosic materials. Because the cellulosic feedstock with the most commercial interest to date is corn stover, the corn stover fermentation pathway was selected for use in the analysis. The corn stover pathway emissions consist of emissions from collection, makeup fertilizer application, transport, ethanol production and distribution. A 30% field collection rate is assumed with 14% loss from field to plant. Conventional till with a cover crop of rye is assumed for land management practices.

Table B-16 provides the GREET1_2015 default field emission parameters that are utilized in the analysis. Table B-17 provides the GREET default ethanol production assumptions that are utilized in this analysis. These assumptions yield CI estimates of less than 10 g CO_2e/MJ. A review of the cellulosic ethanol pathways submitted to ARB for Low Carbon Fuel Standard (LCFS) compliance indicate that a more realistic average value at present is 25 g CO_2e/MJ. Actual yields and the amount of exported electricity are lower than the GREET values. This analysis assumes that cellulosic ethanol has a CI of 25 g CO_2e/MJ.

Table B-16. GREET1_2015 default field assumptions for stover

GREET Default Values	Units	2015-2040
Collection Energy Use	Btu/dry ton	192,500
Transport Energy Use	Btu/dry ton	4,200
Rye Farming Energy Use	Btu/dry ton	51,924
Replacement Nitrogen	g N/dry ton	7,000
Replacement Phosphorus	g P_2O_5/dry ton	2,000
Potassium Use	g K_2O /dry ton	12,000
Herbicide Use (rye)	g/dry ton	582

[111] Federal Register Citation 75 FR 14670

Table B-17. GREET1_2016 ethanol plant operating assumptions

Values	Units	2015	2020	2040
Ethanol Yield	gal/dry ton	85	90	90
Fuel Use	Btu/gal	180	180	180
Exported Electricity (GREET)	kWh/gal	2.4	2.3	2.3

Indirect Land Use Change Emissions

An additional source of emissions for biofuel pathways is referred to as indirect land use change (ILUC). ILUC emissions must be quantified for biofuels derived from grown crops. The emissions arise when land used to grow a crop for uses other than biofuel production is converted to grow feedstock for biofuel production. The indirect impacts of this change (increased cultivation of the displaced crop elsewhere) are accounted for. It is very difficult to accurately quantify ILUC emissions; general equilibrium models of world trade are used to evaluate the impact of changes in corn, sugarcane and soybean cultivation to determine where land use change occurs. Additional modeling is done supplemented by satellite photography to determine the carbon emissions associated with the predicted land use change.

A recent study by ICF[112] for the USDA estimates an ILUC value for corn ethanol of 1.3 to 16.9 gCO2e/MJ. Their result is based on GTAP2013 model runs and a variety of different land use change emission factors. This study utilizes the indirect land use change (ILUC) estimates developed by the California Air Resources Board (ARB) and provided in the LCFS Final Regulation Order dated November 16, 2015[113]. Table B-18 provides the ILUC values for the four biofuels utilized in the present analysis.

Table B-18. ARB ILUC values

Fuel	ILUC (gCO_2e/MJ)
Corn Ethanol	19.8
Sugarcane Ethanol	11.8
Soybean Biodiesel	29.1
Canola Biodiesel	14.5

Ethanol from NG

The current abundant supply of low-cost natural gas might make it an attractive potential feedstock for ethanol production. Coskata and Celanese have pursued this fuel pathway which consists of converting natural gas to synthesis gas (carbon monoxide and hydrogen) followed by conversion of carbon monoxide and hydrogen directly to ethanol over a catalyst. The natural gas feedstock results in an excess of hydrogen gas that provides either process heat to produce synthesis gas or potentially a co-product hydrogen stream. The process is analogous to methanol production from natural gas, which is produced at world scale with either steam

[112] "A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn-Based Ethanol", January 12, 2017, ICF.

[113] California Code of Regulations, Chapter 17 Part 95480

reforming or combined auto-thermal and steam reforming as the means of synthesis gas production. The net stoichiometric reactions are shown below:

$$2CH_4 + 2H_2O \rightarrow 6H_2 + 2CO$$

$$2CO + 4H_2 \rightarrow CH_3CH_2OH + H_2O$$

$$2CH_4 + H_2O \rightarrow CH_3CH_2OH + 2H_2$$

The net reaction for ethanol production results in net products where half of the fuel energy is hydrogen[114]. The net overall reaction for methanol production results in a similar overall stoichiometry where

$$CO + 2\,H_2 \rightarrow CH_3OH$$

In the case of ethanol production, the additional oxygen molecule is converted to water vapor. The overall carbon efficiency for ethanol production is 77%[115] while the efficiency for methanol production[116] is 80%. Thus, the catalytic production of ethanol should be slightly less efficient than methanol production based on the same synthesis gas production route.

This expectation is consistent with preliminary processing data from fuel developers. Without actual yield data, LCA has inferred an ethanol production yield of 0.14 MCF of natural gas per gallon of ethanol from proprietary economic assessments. A separate analysis[117] approximately confirms this yield. This yield is consistent with an overall energy efficiency of 58.6%; for reference, world scale corn ethanol plants have efficiencies ranging from 69 to 71%. With greater thermal integration and on-site power generation from waste synthesis gas an efficiency of 63.7% was assumed and used in the GREET model to estimate the CI for natural gas-based ethanol. Table B-19 provides the GREET default values to produce ethanol from both natural gas and biogas; methanol produced from natural gas is also provided for reference. Because the CI of ethanol produced from NG is higher than the CI of gasoline, it is not considered further in our analysis.

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[114] 46 kg of ethanol x 26.8 MJ/kg ethanol compared with 4 kg of hydrogen x 120 MJ/kg of hydrogen.

[115] 46 kg ethanol x 26.8 MJ/kg/(2 x 16 kg CH_4 x 50 MJ/kg) = 77.1%

[116] 32 kg methanol x 19.9 MJ/(16 kg CH4 x 50 MJ/kg) = 79.6%

[117] "Comparative Economic and Environmental Impacts of Alternative Light-duty Liquid Fuels Produced from Natural Gas", Carnegie Mellon University.

Table B-19. GREET inputs for natural gas to ethanol

Pathway Syngas Source	NG Methanol NG SR	NG Ethanol NG SR	BioGas Ethanol NG SR
Energy Efficiency	70.0%	63.7%	63.7%
Fuel Product			
LHV (MJ/kg)	20	26.8	26.8
Energy (MJ)	35	31.87	31.87
Mass (kg)	1.75	1.19	1.19
Carbon (kg)	0.656	0.621	0.621
Carbon eta	89.9%	85.0%	85.0%
CI (g CO_2/MJ)	98.1	107.7	38.6
MCF/gal	0.118	0.130	0.130

Biogas is also a potential source of ethanol production. Ethanol production facilities could be built at landfills or the biogas could be transmitted by pipeline. Currently much of this biogas is used for CNG applications because biogas to CNG yields a cellulosic RIN credit. The CI of natural gas to ethanol can be as low as 108 g CO_2/MJ and biogas derived ethanol could have a CI below 40 g CO_2/MJ. Potential technology improvements that take advantage of the CO_2 in landfill gas could result in a lower CI.

Summary of CI Values for Each Electricity Grid Mix

With the assumptions described above, the modified GREET model was exercised for three different analysis years (2016, 2020, 2040) and three different electricity grid mixes: AEO2016 with the Clean Power Plan, AEO2016 without the Clean Power Plan, and a 70% non-fossil grid mix. The results are provided below in Table B-20, Table B-21, and Table B-22, with the relative contribution from the WTT, TTW and ILUC components shown. Note that the values shown in the Tables for cellulosic (stover) ethanol are the values emerging from the modified GREET models. As discussed above, a CI value of 25 g CO_2e/MJ is utilized for cellulosic ethanol in the scenario analysis. The higher value is consistent with actual values from the California LCFS program for several cellulosic fuel producers.

For most fuels, the CI values decrease over time due to decreases in electric power carbon content. One exception to this rule is petroleum fuels; gasoline and diesel values increase over time mainly due to default GREET assumptions regarding crude oil source and resulting impacts on refining efficiency.

Fuels that are a mixture of different feedstocks such as biodiesel, ethanol, and CNG have composite CI values based on assumed feedstock share profiles over time. These feedstock shares are provided in the *Fuel Blend Assumptions* section of the main report.

Table B-20. CI values for AEO2016 reference case with CPP

Base Case	2016			2020			2040			WTW CI, gCO_2e/MJ		
	WTT	TTW	ILUC	WTT	TTW	ILUC	WTT	TTW	ILUC	2016	2020	2040
Gasoline Blendstock	19.2	74.0	0.0	19.6	74.0	0.0	19.5	74.0	0.0	93.1	93.6	93.5
HOF 30 Blendstock	20.2	74.0	0.0	20.5	74.0	0.0	20.2	74.0	0.0	94.1	94.5	94.2
E70 Blendstock	11.5	80.7	0.0	11.5	80.7	0.0	11.4	80.7	0.0	92.2	92.1	92.0
ULSD	15.6	75.6	0.0	16.1	75.6	0.0	16.0	75.6	0.0	91.2	91.7	91.6
Ethanol MW Corn Avg	50.7	0.1	19.8	47.7	0.1	19.8	44.9	0.1	19.8	70.6	67.6	64.8
Ethanol Sugarcane	26.7	0.1	11.8	25.5	0.1	11.8	25.5	0.1	11.8	38.6	37.4	37.4
Ethanol Stover	4.0	0.1	0.0	4.7	0.1	0.0	6.8	0.1	0.0	4.0	4.8	6.9
Biodiesel Soybean	23.0	3.9	29.1	22.6	3.9	29.1	22.1	3.9	29.1	56.0	55.6	55.1
Biodiesel Canola	31.2	3.9	14.5	30.8	3.9	14.5	30.3	3.9	14.5	49.6	49.2	48.7
Biodiesel Tallow	29.1	3.9	0.0	28.3	3.9	0.0	27.2	3.9	0.0	33.0	32.3	31.1
Biodiesel Corn Oil	11.7	3.9	0.0	11.2	3.9	0.0	10.5	3.9	0.0	15.7	15.1	14.4
Renew Diesel Soy	23.3	0.0	29.1	23.1	0.0	29.1	22.6	0.0	29.1	52.4	52.2	51.7
Renew Diesel Canola	31.2	0.0	14.5	31.0	0.0	14.5	30.4	0.0	14.5	45.7	45.5	44.9
Renew Diesel Corn Oil	12.5	0.0	0.0	12.1	0.0	0.0	11.4	0.0	0.0	12.5	12.1	11.4
CNG	19.4	62.2	0.0	19.0	62.2	0.0	18.2	62.2	0.0	81.6	81.1	80.4
Electricity	154.0	0.0	0.0	136.4	0.0	0.0	104.3	0.0	0.0	154.0	136.4	104.3
Hydrogen-NG	119.8	0.0	0.0	115.8	0.0	0.0	110.2	0.0	0.0	119.8	115.8	110.2
Hydrogen-Elec	246.3	0.0	0.0	201.9	0.0	0.0	154.4	0.0	0.0	246.3	201.9	154.4

Table B-21. CI values for AEO2016 reference case without CPP

AEO2016 no CPP	2016			2020			2040			WTW CI, gCO_2e/MJ		
	WTT	TTW	ILUC	WTT	TTW	ILUC	WTT	TTW	ILUC	2016	2020	2040
Gasoline Blendstock	19.2	74.0	0.0	19.7	74.0	0.0	19.9	74.0	0.0	93.1	93.6	93.8
HOF 30 Blendstock	20.2	74.0	0.0	20.5	74.0	0.0	20.6	74.0	0.0	94.1	94.5	94.6
E70 Blendstock	11.5	80.7	0.0	11.5	80.7	0.0	11.4	80.7	0.0	92.2	92.1	92.1
ULSD	15.6	75.6	0.0	16.1	75.6	0.0	16.4	75.6	0.0	91.2	91.7	91.9
Ethanol MW Corn Avg	50.7	0.1	19.8	47.8	0.1	19.8	45.8	0.1	19.8	70.6	67.7	65.7
Ethanol Sugarcane	26.7	0.1	11.8	25.5	0.1	11.8	25.5	0.1	11.8	38.6	37.4	37.4
Ethanol Stover	4.0	0.1	0.0	4.6	0.1	0.0	5.3	0.1	0.0	4.0	4.7	5.4
Biodiesel Soybean	23.0	3.9	29.1	22.6	3.9	29.1	22.4	3.9	29.1	56.0	55.6	55.5
Biodiesel Canola	31.2	3.9	14.5	30.8	3.9	14.5	30.6	3.9	14.5	49.6	49.2	49.1
Biodiesel Tallow	29.1	3.9	0.0	28.4	3.9	0.0	28.0	3.9	0.0	33.0	32.3	32.0
Biodiesel Corn Oil	11.7	3.9	0.0	11.2	3.9	0.0	11.0	3.9	0.0	15.7	15.2	14.9
RD Soybean	23.3	0.0	29.1	23.1	0.0	29.1	22.9	0.0	29.1	52.4	52.2	52.0
RD Canola	31.2	0.0	14.5	31.0	0.0	14.5	30.8	0.0	14.5	45.7	45.5	45.3
RD Corn Oil	12.5	0.0	0.0	12.1	0.0	0.0	11.9	0.0	0.0	12.5	12.1	11.9
CNG	19.4	62.2	0.0	19.0	62.2	0.0	18.8	62.2	0.0	81.6	81.2	80.9
Electricity	154.0	0.0	0.0	137.9	0.0	0.0	126.9	0.0	0.0	154.0	137.9	126.9
Hydrogen-NG Reforming	119.8	0.0	0.0	116.0	0.0	0.0	114.1	0.0	0.0	119.8	116.0	114.1
Hydrogen-Electrolysis	246.34	0	0	204.11	0	0	187.78	0	0	246.3	204.1	187.8

Table B-22. CI values for 70% non-fossil case

70% Non-Fossil by 2040	2016			2020			2040			WTW CI, gCO_2e/MJ		
	WTT	TTW	ILUC	WTT	TTW	ILUC	WTT	TTW	ILUC	2016	2020	2040
Gasoline Blendstock	19.2	74.0	0.0	19.3	74.0	0.0	18.4	74.0	0.0	93.1	93.3	92.4
HOF 30 Blendstock	20.2	74.0	0.0	20.1	74.0	0.0	19.0	74.0	0.0	94.1	94.1	92.9
E70 Blendstock	11.5	80.7	0.0	11.4	80.7	0.0	11.2	80.7	0.0	92.2	92.1	91.8
ULSD	15.6	75.6	0.0	15.8	75.6	0.0	15.0	75.6	0.0	91.2	91.4	90.6
Ethanol MW Corn Avg	50.7	0.1	19.8	46.9	0.1	19.8	42.4	0.1	19.8	70.6	66.8	62.2
Ethanol Sugarcane	26.7	0.1	11.8	25.4	0.1	11.8	25.3	0.1	11.8	38.6	37.3	37.2
Ethanol Stover	4.0	0.1	0.0	6.0	0.1	0.0	10.8	0.1	0.0	4.0	6.0	10.8
Biodiesel Soybean	23.0	3.9	29.1	22.3	3.9	29.1	21.1	3.9	29.1	56.0	55.3	54.2
Biodiesel Canola	31.2	3.9	14.5	30.4	3.9	14.5	29.2	3.9	14.5	49.6	48.9	47.7
Biodiesel Tallow	29.1	3.9	0.0	27.6	3.9	0.0	24.9	3.9	0.0	33.0	31.6	28.8
Biodiesel Corn Oil	11.7	3.9	0.0	10.7	3.9	0.0	9.1	3.9	0.0	15.7	14.7	13.0
RD Soybean	23.3	0.0	29.1	22.7	0.0	29.1	21.6	0.0	29.1	52.4	51.8	50.7
RD Canola	31.2	0.0	14.5	30.6	0.0	14.5	29.4	0.0	14.5	45.7	45.1	43.9
RD Corn Oil	12.5	0.0	0.0	11.6	0.0	0.0	9.9	0.0	0.0	12.5	11.6	9.9
CNG	19.4	62.2	0.0	18.5	62.2	0.0	16.7	62.2	0.0	81.6	80.7	78.9
Electricity	154.0	0.0	0.0	116.4	0.0	0.0	41.7	0.0	0.0	154.0	116.4	41.7
Hydrogen-NG Reforming	119.8	0.0	0.0	112.3	0.0	0.0	99.4	0.0	0.0	119.8	112.3	99.4
Hydrogen-Electrolysis	246.34	0	0	172.19	0	0	61.66	0	0	246.3	172.2	61.7

Appendix C Carbon Intensity Estimates for the California Analysis

For the California analysis, CI values were taken directly from ARB's most recent LCFS compliance scenario.[118] In addition to CI values for a range of fuel/feedstock combinations, ARB also provides projected volumes of different types of ethanol, biodiesel and CNG so that composite CI values can be calculated. LCA used CA-GREET2 to calculate electricity and hydrogen CI values.

Table C-1 provides the CI values for California reformulated blendstock for oxygenate blending (CARBOB), ultra low-sulfur diesel (ULSD), Fossil CNG, renewable natural gas (RNG), average biodiesel (BD), and renewable diesel (RD). Note that CARBOB's CI is ~ 7 gCO2e/MJ higher than the U.S. blendstock value. ARB employs the OPGEE model to calculate the emissions from crude recovery and transport. The crude portion of the CARB pathway is approximately 12 g/MJ as in contrast to 6.5 g/MJ for the U.S. average blendstock. ARB's compliance scenario assumes that the current share of RNG in CNG is 44% followed by a steady increase to 93% by 2025. In this analysis, it is assumed that the 93% share is maintained through 2050.

Table C-1. ARB projected CI values for petroleum, BD, RD and CNG

	ARB Illustrative Compliance Scenario CI Values, gCO2e/MJ					
	CARBOB	ULSD	Average BD	Average RD	Fossil CNG	Renew CNG
2015	99	98	20	35	71	20
2016	101	103	20	30	78	20
2017	101	103	20	30	78	20
2018	101	103	19	30	78	20
2019	101	103	19	30	78	19
2020	101	103	18	30	78	19
2021	101	103	18	30	78	19
2022	101	103	17	30	78	19
2023	101	103	17	30	78	18
2024	101	103	16	30	78	18
2025	101	103	16	30	78	18

ARB's CI values for the different types of ethanol are shown in Table C-2. The "corn+" category is for ethanol derived from corn/sorghum and corn/sorghum/wheat mixtures. Table C-3 provides ARB's projected volumes of ethanol by feedstock type through 2025. It is assumed for the base case that the 2025 shares are maintained through 2050. A low-CI ethanol case is also considered. Figure C-1 provides the relative shares of the different ethanol feedstocks for this case. For 2015-2025, the shares are the same as in the BAU case; after 2025, cellulosic shares steadily increase to 70% of the total. It is assumed that corn and corn+ provide a minimum of 30% of the ethanol through 2050. The result is decreasing shares of imported sugarcane and molasses.

[118] ARB LCFS Illustrative Compliance Scenario, 4-1-15.

Table C-2. ARB projected CI values for ethanol (with ILUC)

	ARB Ethanol CI Values, gCO2e/MJ				
	Corn	Cane	Corn+	Cellulosic	Molasses
2015	83	70	74	20	23
2016	70	44	68	20	33
2017	69	44	67	20	33
2018	67	43	66	20	36
2019	66	43	65	20	36
2020	65	42	64	20	36
2021	64	42	63	20	35
2022	63	41	62	20	35
2023	62	41	61	20	35
2024	61	40	61	20	34
2025	60	40	60	20	34

Table C-3. ARB projected ethanol shares

	ARB Projected Ethanol Shares				
	Corn	Cane	Corn+	Cell	Molasses
2015	79%	10%	10%	0%	1%
2016	74%	13%	10%	0%	3%
2017	68%	17%	12%	1%	3%
2018	57%	24%	12%	3%	4%
2019	51%	27%	12%	5%	4%
2020	47%	30%	12%	7%	4%
2021	39%	33%	11%	13%	4%
2022	36%	33%	11%	16%	4%
2023	31%	33%	12%	20%	4%
2024	27%	34%	12%	24%	4%
2025	22%	34%	12%	27%	4%

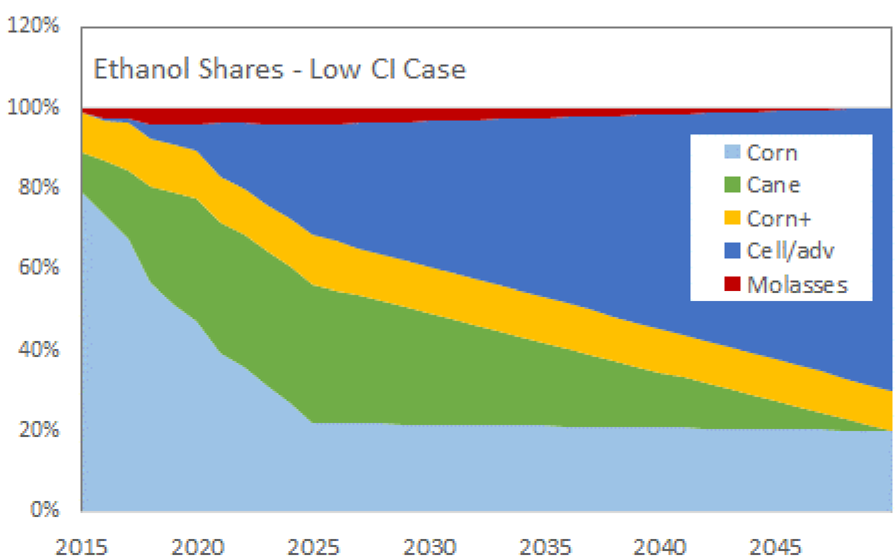

Figure C-1. Ethanol shares through 2050 for the low-CI ethanol case

LCA utilized the CA-GREET2 model to calculate CI values for electricity over time. The first step was to project the grid resource mix. CEC's total system power report[119] for 2015 was utilized; it was assumed that the 2016 mix was the same as the 2015 mix. In 2025, PG&E's Diablo Canyon is slated to shut down, bringing California's nuclear generation to 0. PG&E (44% of total supply) has pledged to replace this power with 55% renewables. In 2030, the grid is to be 50% renewable (PG&E at 55%). For the base case, we assume 2050 is the same as 2030. For the low-CI case, it is assumed that the grid is 70% non-fossil. These grid mix projections are tabulated in Table C-4 and provided graphically in Figure C-2. Note that the 70% non-fossil case provides a 22% decrease in CI relative to the base case in 2050. Table C-5 provides a comparison of California and U.S. electricity CI values. Without the CPP, the U.S. electricity CI is double the CA base case value by 2030.

Table C-4. Assumed California electricity resource mix

	Oil	Gas	Coal	Nuclear	Biomass	Other Renew
2016	0%	49%	7%	11%	3%	30%
2025	0%	42%	2%	0%	3%	53%
2030	0%	40%	0%	0%	3%	57%
2050 (70% NF)	0%	30%	0%	0%	3%	67%

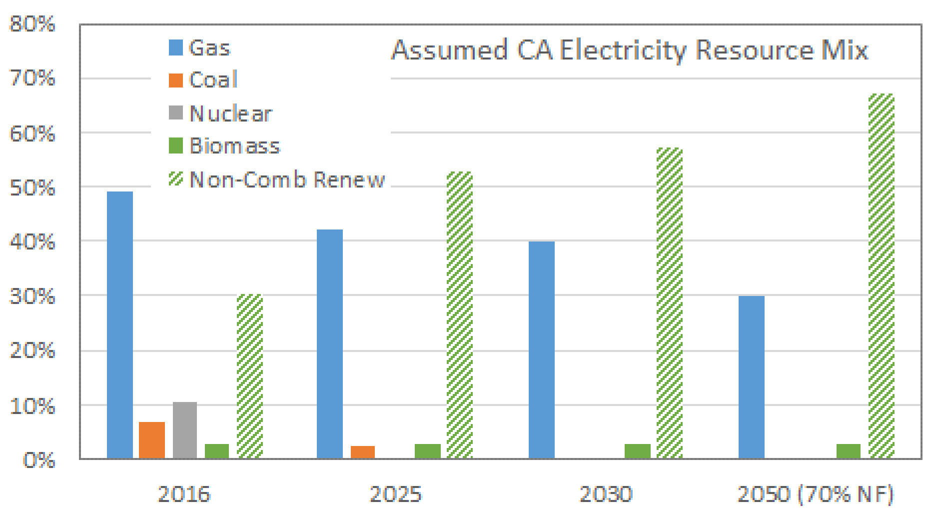

Figure C-2. Electricity grid mix assumption

[119] http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html

Table C-5. Electricity CI values

	California gCO_2e/MJ	California, 70% NF gCO_2e/MJ	U.S. w/CPP gCO_2e/MJ	U.S. no CPP gCO_2e/MJ
2016	99	99	154	154
2025	74	74	136	138
2030-2050	64	64-50		
2040-2050			104	127

State law[120] requires that 33% of all hydrogen sold be produced from renewable resources. For this analysis, it is assumed that 33% is produced via electrolysis using 100% renewable electricity. The balance is assumed to be on-site natural gas steam reforming. Table C-6 provides the CA-GREET2 results for these two pathways and the resulting composite CI.

Table C-6. Assumed hydrogen CI values

CI, gCO2e/MJ	100% Renewable Electrolysis	On-Site NG Steam Reforming	Composite Hydrogen
2016	12.8	109.3	77.4
2025	9.7	106.5	74.5
2030-2050 (base case)	8.3	105.3	73.3
2050 (70% NF)	6.4	103.6	71.5

[120] CA Senate Bill 1505, 2006

Appendix D Vehicle Market Shares for U.S. Scenario Analysis

Four main scenarios were evaluated and compared to a business-as-usual (BAU) case. There is one scenario for each key vehicle technology (BEV, PHEV, dedicated E85 PHEV, and dedicated E85 HEV). Note that the dedicated E85 vehicles are designed to take advantage of the octane boost associated with high ethanol blends so have a better fuel economy than an FFV. These vehicles are fueled exclusively with E85. Table D-1 Summarizes the scenarios considered.

Table D-1. New vehicle market share assumptions for U.S. analysis scenarios

Scenario	2050 LDA Market Share	2050 LDT Market Share
BAU	85% Gasoline ICE 1% Diesel 6% HEV 3% PHEV 4% BEV 1% H2 FCV	94% Gasoline ICE 2% Diesel 1% HEV 1% PHEV 1% BEV 1% FCV
1. Max BEV	70% BEV 15% E85 HEV 4.3% Gasoline ICE All others BAU	45% BEV 45% E85 HEV 4.6% Gasoline ICE All others BAU
2a. Max PHEV/E85 HEV	80% PHEV 4.4% E85 HEV 4.3% Gasoline ICE All others BAU	45% PHEV 45% E85 HEV 4.6% Gasoline ICE All others BAU
2b. Max PHEV/CNG	Same as 2a	45% PHEV 46% CNG 4.6% Gasoline ICE All others BAU
3. Max E85 PHEV	81% E85 PHEV 4.3% Gasoline ICE All others BAU	45% E85 PHEV 45% E85 HEV 4.6% Gasoline ICE All others BAU
4. Max E85 HEV	81% E85 HEV 4.3% Gasoline ICE All others BAU	90% E85 HEV 4.6% Gasoline ICE All others BAU

The following guidelines were used to adjust new vehicle market shares:

- To ensure a fair comparison between scenarios, gasoline ICE market shares in each scenario were decreased to 1.8% for LDA and 2.4% for LDT.
- All other technology shares were maintained at BAU levels except LDT FFV. The 2050 BAU market share for LDT FFVs is 19%. This was decreased to 3% to allow significant penetration of alternative vehicles.
- Because BEV market share is limited by homes with EVSE access, for LDA the maximum possible market share is set at 70% for BEVs and 80% for PHEVs.

- For LDTs, BEVs do not provide towing capability. It was assumed that maximum LDT market share for BEVs and PHEVs is 45%. Dedicated E85 HEVs and NGVs are also sold.
- It is assumed that dedicated E85 HEVs have a faster ramp up to goal market penetration than electrification options because they are less expensive

Figure D-1 and Figure D-2 illustrate the market shares of new light auto and light truck sales for Scenario 1 (Max BEV). The primary LDA sales are BEVs, followed by dedicated E85 HEVs since 100% market share is not realistic. As noted above, maximum LDT BEV market share was limited to 45%. The 2050 market share for BEVs is the same as the assumed market share of LDT E85 HEVs.

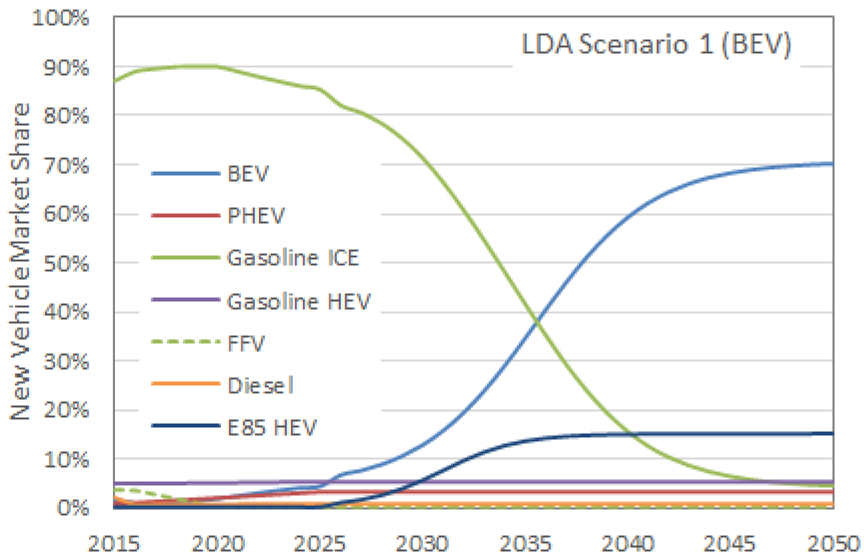

Figure D-1. LDA assumed new vehicle market shares for U.S. Scenario 1

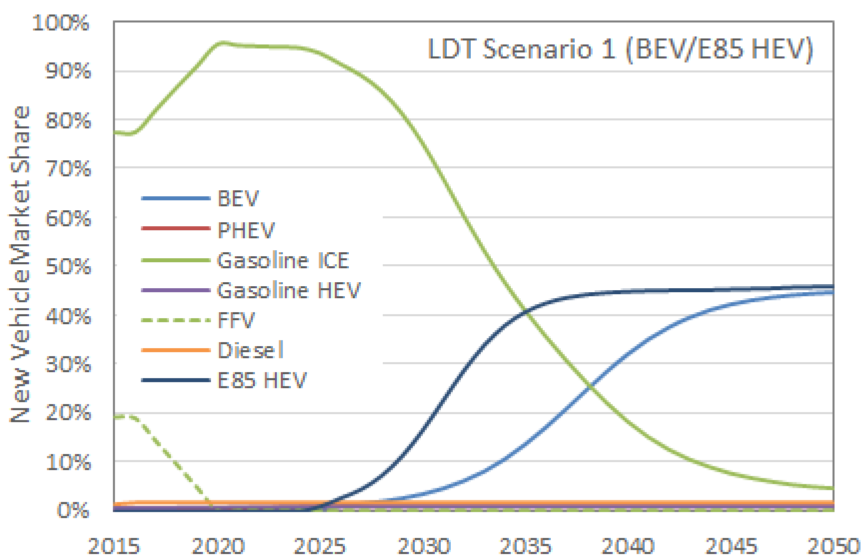

Figure D-2. LDT assumed new vehicle market shares for U.S. Scenario 1

Scenario 2 is the Max PHEV scenario. The new vehicle market share assumptions for LDAs are provided in Figure D-3 while the LDT assumptions for Scenario 2a and Scenario 2b are shown in Figure D-4 and Figure D-5, respectively. As mentioned above, the maximum PHEV market share for LDTs is limited to 45%. In Scenario 2a, LDT PHEVs are supplemented with dedicated E85 HEVs while in Scenario 2b the PHEVs are supplemented with CNG vehicles.

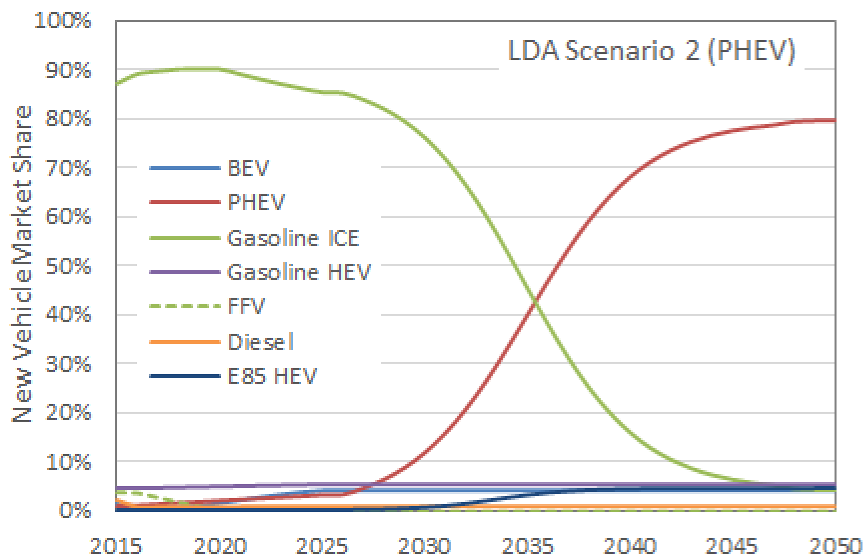

Figure D-3. LDA assumed new vehicle market shares for U.S. Scenario 2a and 2b

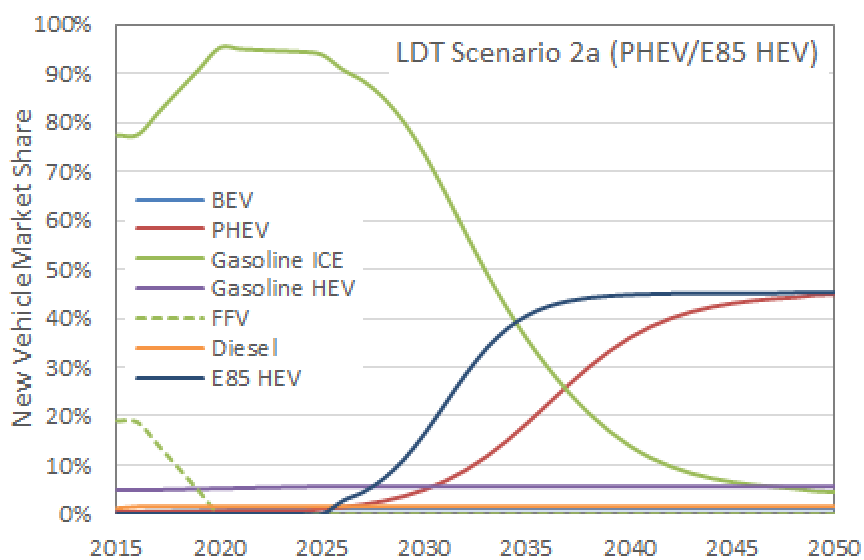

Figure D-4. LDT assumed new vehicle market shares for U.S. Scenario 2a

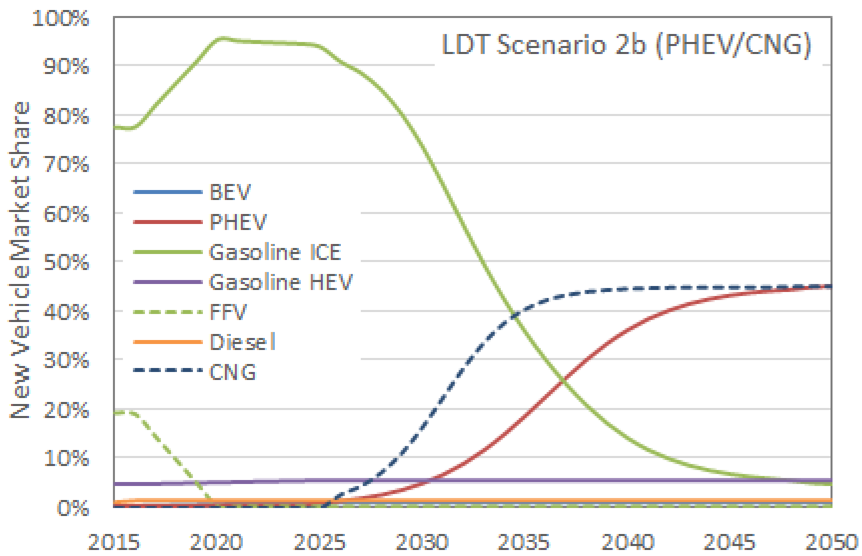

Figure D-5. LDT assumed new vehicle market shares for U.S. Scenario 2b

Scenario 3 is like Scenario 2 except that it focuses on dedicated E85 PHEVs rather than gasoline PHEVs. Figure D-6 illustrates the assumed market share assumptions for LDAs while Figure D-7 provides the LDT assumptions.

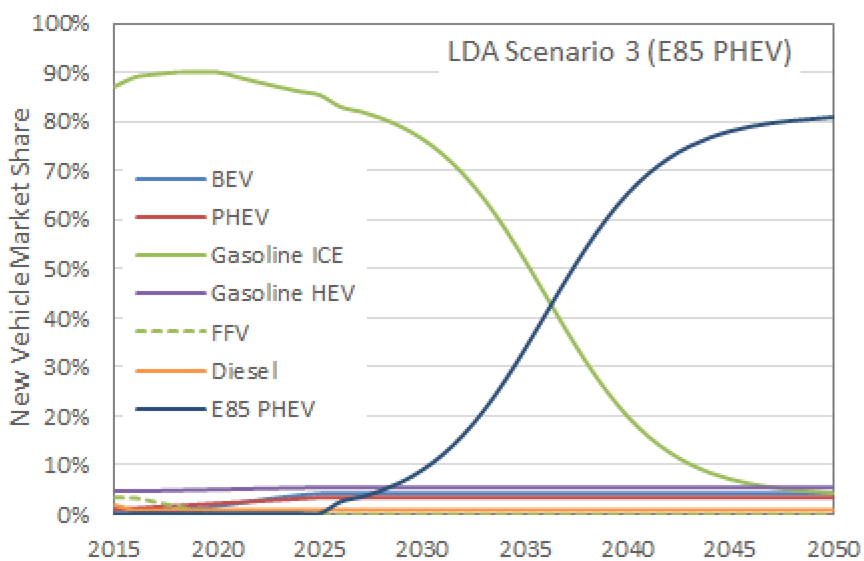

Figure D-6. LDA assumed new vehicle market shares for U.S. Scenario 3

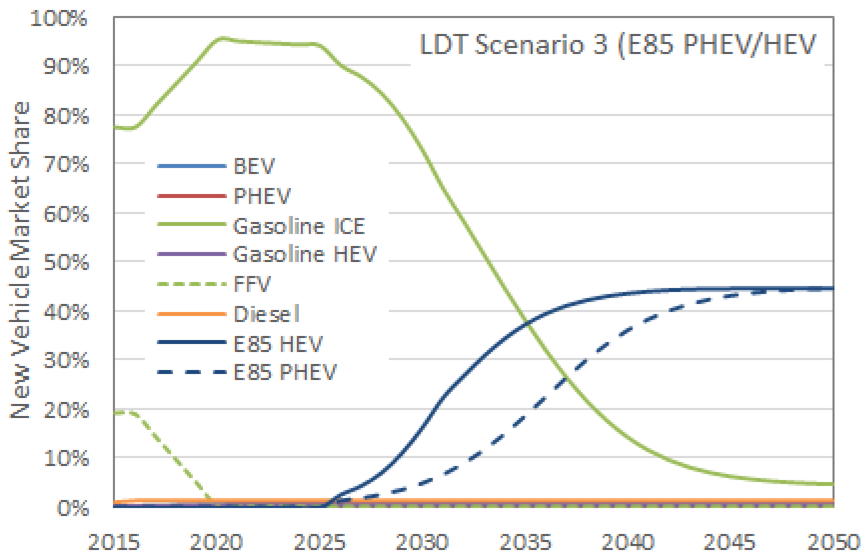

Figure D-7. LDT assumed new vehicle market shares for U.S. Scenario 3

Scenario 4 focuses on maximum penetration of dedicated E85 HEVs. The assumed market shares of new LDAs are provided in Figure D-8 while the LDT market shares are illustrated in Figure D-9.

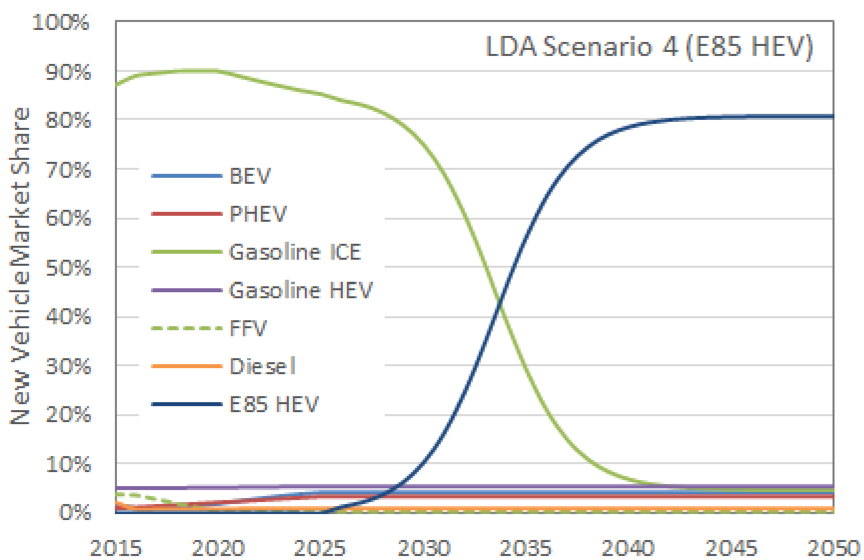

Figure D-8. LDA assumed new vehicle market shares for U.S. Scenario 4

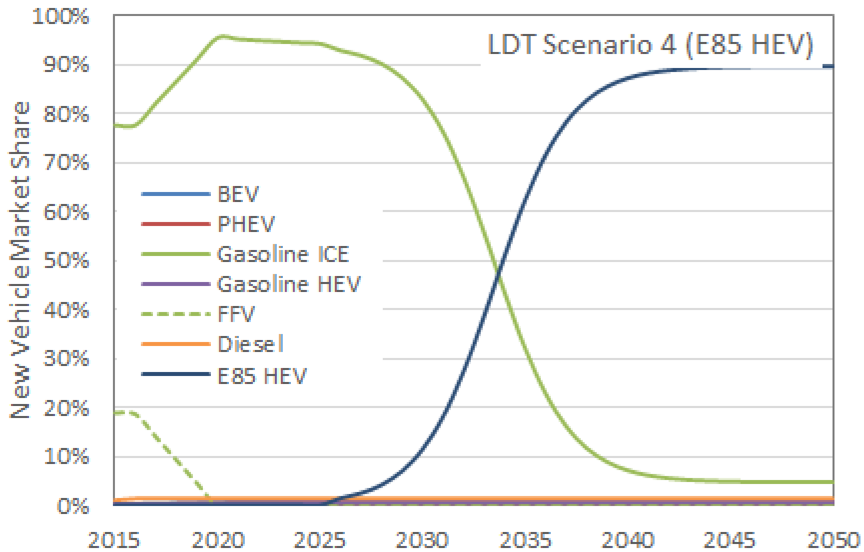

Figure D-9. LDT assumed new vehicle market shares for U.S. Scenario 4

Appendix E Vehicle Market Shares for CA Scenario Analysis

Consistent with the U.S. analysis, the California analysis considers four main scenarios. There is one scenario for each key vehicle technology: BEV, PHEV, dedicated E85 PHEV, and dedicated E85 HEV. Table E-1 provides the new vehicle market share values in 2050 for each scenario.

Table E-1. New vehicle market share assumptions for California analysis scenarios

Scenario	2050 LDA Market Share	2050 LDT Market Share
1. Max BEV	70% BEV 2% Gasoline ICE All others BAU	43% BEV 43% E85 HEV 2% Gasoline ICE All others BAU
2a. Max PHEV/E85 HEV	75% PHEV 2% Gasoline ICE All others BAU	45% PHEV 45% E85 HEV 2% Gasoline ICE All others BAU
2b. Max PHEV/CNG	Same as 2a	45% PHEV 46% CNG 2% Gasoline ICE All others BAU
3. Max E85 PHEV	65% E85 PHEV 2% Gasoline ICE All others BAU	43% E85 PHEV 43% E85 HEV 2% Gasoline ICE All others BAU
4. Max E85 HEV	65% E85 HEV 2% Gasoline ICE All others BAU	83% E85 HEV 2% Gasoline ICE All others BAU

The following guidelines were used to adjust new vehicle market shares:

- To ensure a fair comparison between scenarios, gasoline ICE market shares in each scenario were decreased to 2% for LDA and LDT.
- All other technology shares were maintained at BAU levels.
- Because BEV market share is limited by homes with EVSE access, it is assumed that maximum possible BEV market share is 70%, and maximum PHEV market share is 80% for LDA.
- Because electrification is not currently compatible with towing capability, it was assumed that maximum LDT market share for BEVs and PHEVs is 45%. To maximize LDT alternative vehicles, PHEVs and BEVs were supplemented with E85 HEVs or NGVs.
- It is assumed that E85 HEVs and NGVs have a faster market penetration than electrification options

Figure E-1 and Figure E-2 illustrate the assumed LDA and LDT new vehicle market shares for Scenario 1. Our guidelines limit the maximum BEV penetration to 45%, but the California BAU PHEV shares were higher than in the U.S. analysis. To limit total electric drive market share to 45% for LDTs, the maximum BEV market share was limited to approximately 42%. As in the U.S. analysis, LDT market shares were supplemented with dedicated E85 HEVs.

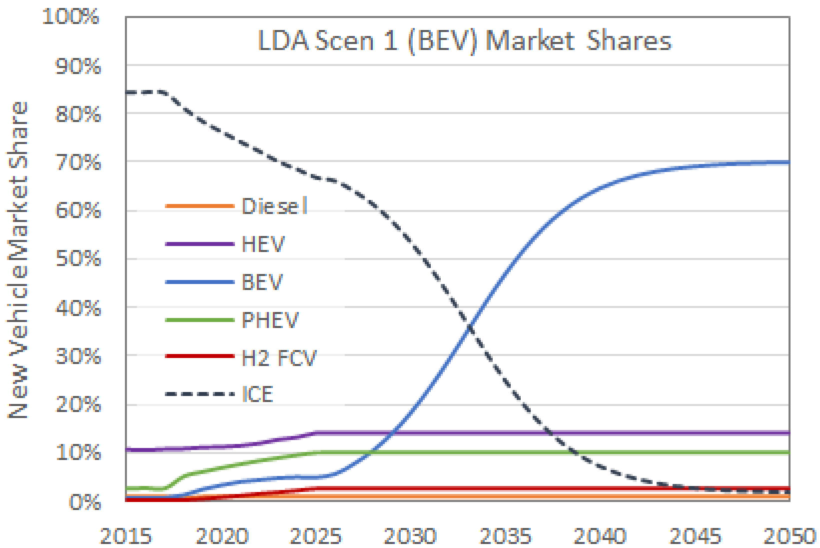

Figure E-1. LDA assumed new vehicle market shares for CA Scenario 1

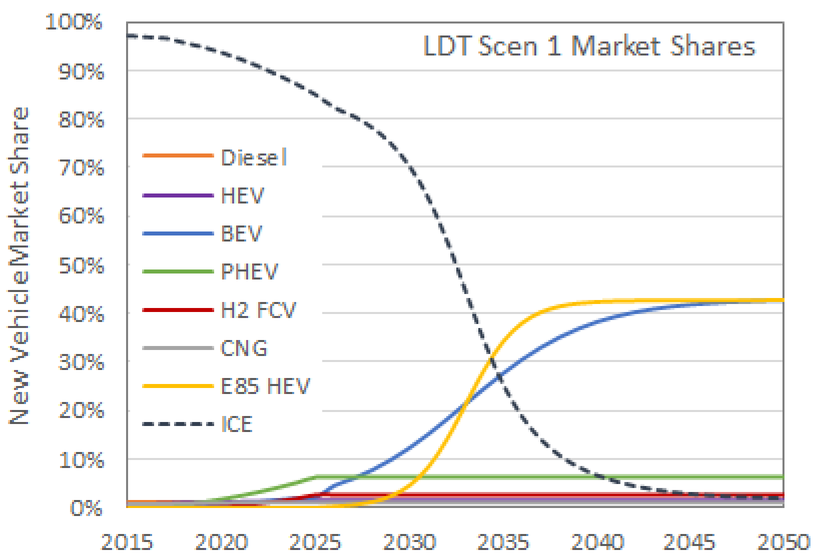

Figure E-2. LDT assumed new vehicle market shares for CA Scenario 1

Figure E-3 provides the LDA market shares for Scenario 2 (max PHEV). Note that in the U.S. analysis, additional shares of dedicated E85 HEVs were assumed to maximize the number of alternative vehicles sold. However, because the California BAU has so many HEVs in the out years, it wasn't possible to add more alternative vehicle market share. The LDT market share assumptions for Scenario 2a (Max PHEV/Max E85 HEV) are provided in Figure E-4 while market share assumptions for Scenario 2b (Max PHEV/Max CNG) are provided in Figure E-5.

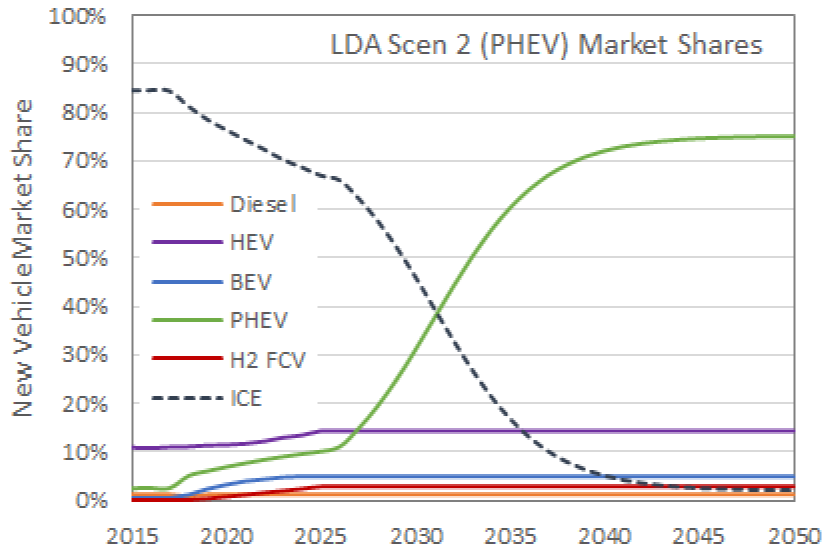

Figure E-3. LDA assumed new vehicle market shares for CA Scenario 2a and 2b

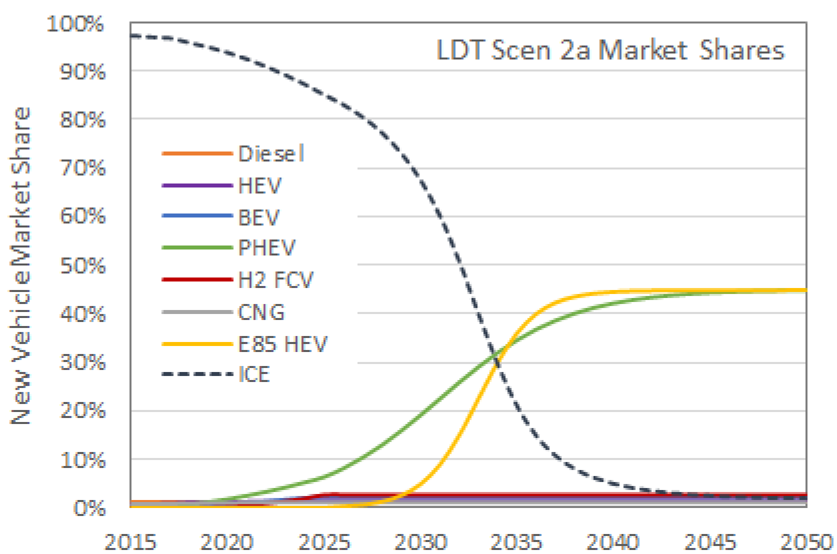

Figure E-4. LDT assumed new vehicle market shares for CA Scenario 2a

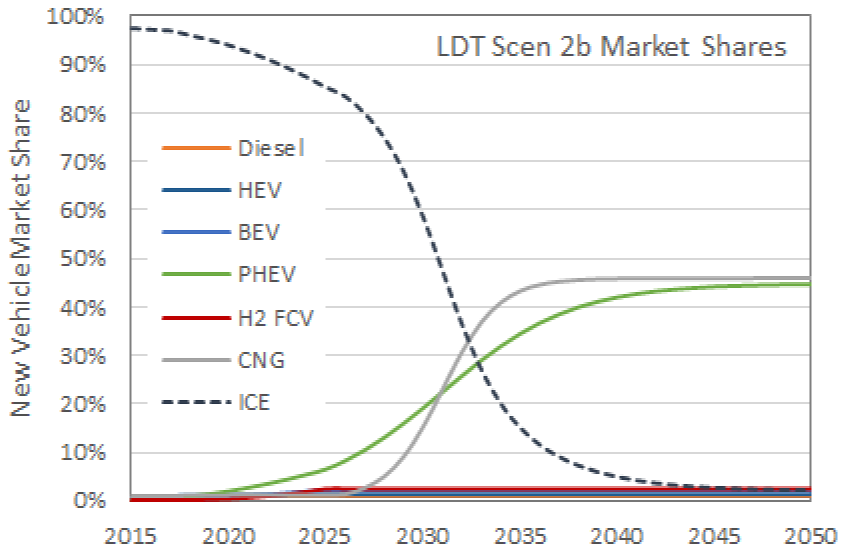

Figure E-5. LDT assumed new vehicle market shares for CA Scenario 2b

Scenario 3 assumes the maximum number of dedicated E85 PHEVs are sold. For LDA (Figure E-6), gasoline PHEVs are maintained at BAU levels while E85 PHEVs are increased until the combined total reaches 75% by 2050. Similarly, total LDT PHEV market share (Figure E-7) is not allowed to exceed 45%.

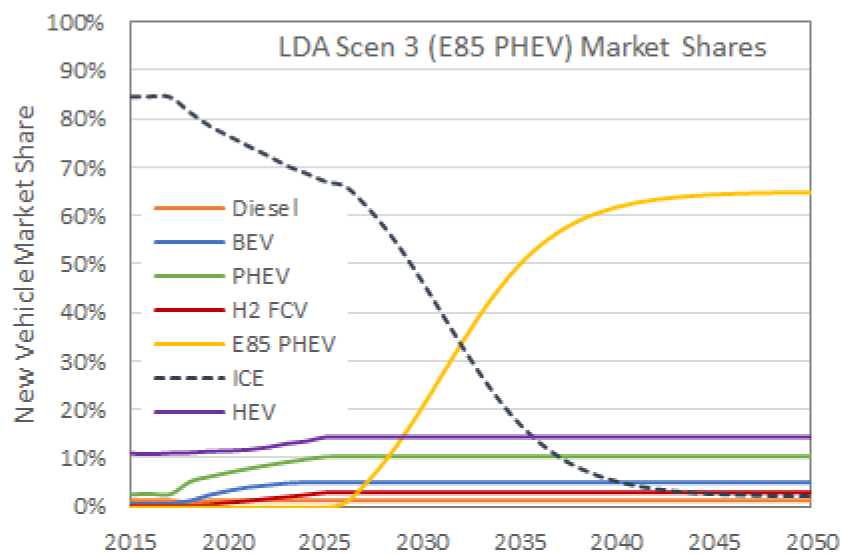

Figure E-6. LDA assumed new vehicle market shares for CA Scenario 3

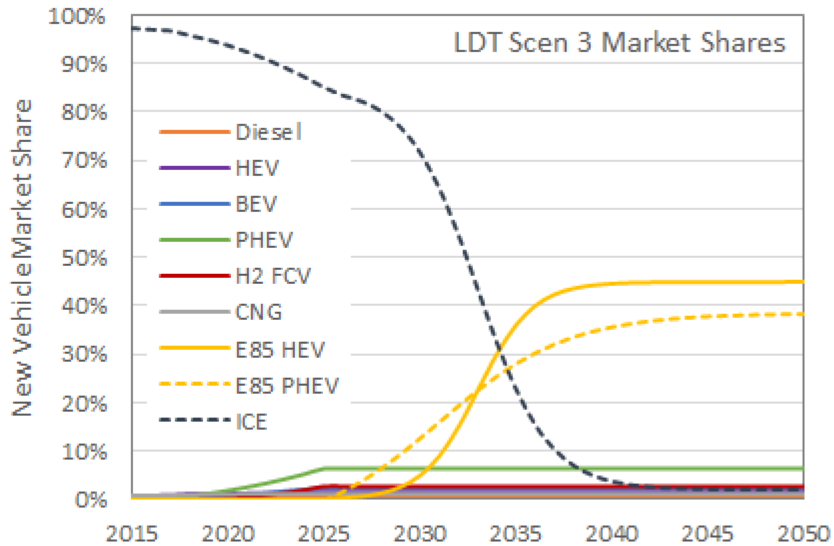

Figure E-7. LDT assumed new vehicle market shares for CA Scenario 3

Scenario 4 features the maximum penetration of dedicated E85 HEVs. BAU levels of HEV, BEV and PHEV are maintained with gasoline ICEs reduced in place of E85 HEVs. For LDA (Figure E-8), 65% E85 HEV is achieved by 2050 and for LDT (Figure E-9), more than 80% new vehicle market share is assumed.

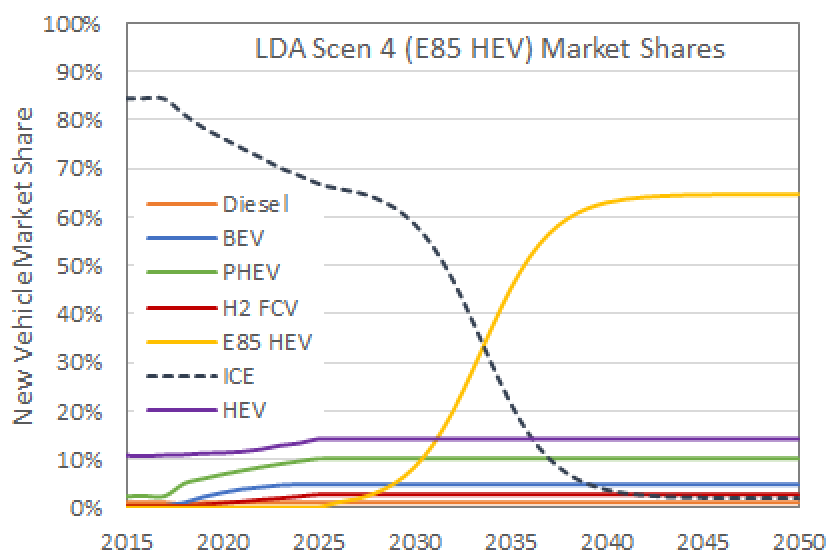

Figure E-8. LDA assumed new vehicle market shares for CA Scenario 4

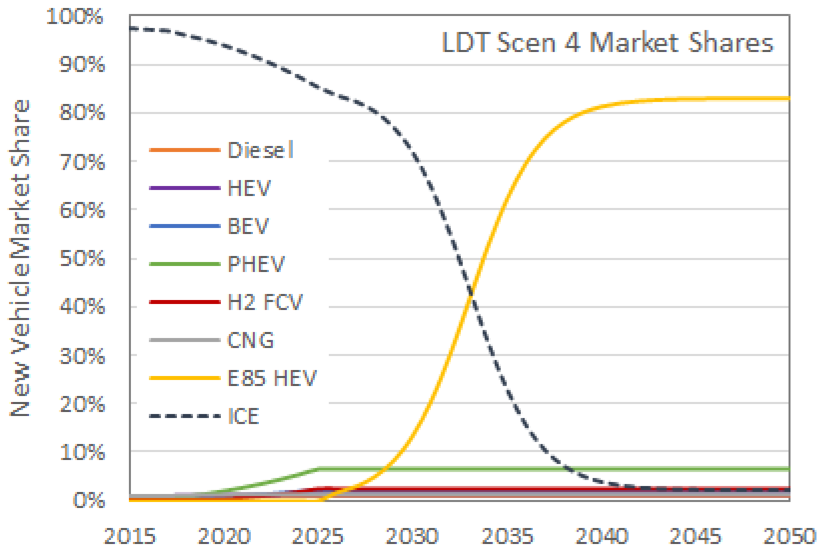

Figure E-9. LDT assumed new vehicle market shares for CA Scenario 4