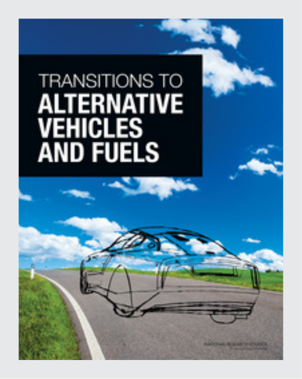

Transitions to Alternative Vehicles and Fuels (2013)

DETAILS

394 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-26852-3 | DOI 10.17226/18264

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SUGGESTED CITATION

National Research Council 2013. *Transitions to Alternative Vehicles and Fuels*. Washington, DC: The National Academies Press. https://doi.org/10.17226/18264.

TRANSITIONS TO ALTERNATIVE VEHICLES AND FUELS

Committee on Transitions to Alternative Vehicles and Fuels

Board on Energy and Environmental Systems

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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This study was supported by Contract DE-DT001481, TO#2, between the National Academy of Sciences and the U.S. Department of Energy. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-26852-3
International Standard Book Number-10: 0-309-26852-4
Library of Congress Control Number: 2013932897

Copies of this report are available
in limited supply, free of charge, from:

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500 Fifth Street, NW
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Washington, DC 20001
(800) 624-6242 or (202) 334-3313
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Preface

The U.S. light-duty vehicle fleet is responsible for about half the petroleum consumed in this nation and about 17 percent of its greenhouse gas emissions. Concerns over national security and climate change have increased interest in alternative ways to power the fleet.

Many technologies, with widely varying levels of current capability, cost, and commercialization, can reduce light-duty vehicle petroleum consumption, and most of these also reduce greenhouse gas emissions. However, any transition to achieve high levels of reduction is likely to take decades. The timeframe of this study goes out to 2050. Projecting the cost and performance of technologies out that far entails many uncertainties. The technical issues alone are extraordinarily complex and interrelated. Further, its statement of task also asked the Committee on Transitions to Alternative Vehicles and Fuels to consider the related policy options.

The committee's analyses, while exploratory and not definitive, having significant uncertainty, indicate that the costs and benefits of large reductions in petroleum consumption and greenhouse gas emissions will both be substantial. Its work also suggests that policy will be an essential element in achieving these reductions. Alternative vehicles and some fuels will be more expensive than their current equivalents, at least for several decades, and advanced technology could be used for increased power or other purposes rather than be focused solely on reducing petroleum use and greenhouse gas emissions. Thus, it is critical to have a clear vision of the options and how they might be implemented if progress is to be made efficiently with a minimum of disruption and a maximum of net benefits. This report explores those options and the related issues, and it sheds light on the decisions the nation may be making.

The members of the study committee worked extraordinarily hard on this task. I am very grateful for their efforts. They represent a remarkably broad and accomplished group of experts. Given the complex nature of the task at hand, producing a report that was satisfactory in every detail to every member was challenging. Given the difficulty we have had in achieving consensus, I will not attempt to summarize the result here. The report speaks for itself.

The committee and I greatly appreciate the efforts made by our highly qualified consultants and the many others who contributed directly to our deliberations via presentations and discussions and the many authors on whose work we relied.

The committee operated under the auspices of the NRC's Board on Energy and Environmental Systems. We owe a special debt of gratitude to James Zucchetto, Alan Crane, Evonne Tang, David Cooke, and Alice Williams of the NRC staff. In spite of what must have seemed like an endless succession of in-person and conference call consultations among the full committee and working groups, meetings to gather information, and revision of the text, their energy and professionalism never wavered. The committee and I personally offer our heartfelt thanks.

Douglas M. Chapin, *Chair*
Committee on Transitions to
Alternative Vehicles and Fuels

Acknowledgments

The Committee on Transitions to Alternative Vehicles and Fuels is grateful to the many individuals who contributed their time and efforts to this National Research Council (NRC) study.

The presentations at committee meetings provided valuable information and insights that enhanced the committee's understanding of the technologies and barriers involved. The committee thanks the following individuals who provided briefings:

Patrick Davis, U.S. Department of Energy,
Phillip Patterson, U.S. Department of Energy,
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Sascha Simon, Mercedes Benz,
Ben Knight, Honda,
Dan Sperling, University of California, Davis, and
Reiko Takemasa, Pacific Gas and Electric Company.

The committee owes special thanks to Michael Ramage (NAE) and James Katzer (NAE), who generously volunteered their time and expertise to assist in many complex and difficult issues. This report has benefited greatly from their contributions. The members of the committee and the staff deeply regret the death of Jim Katzer in November 2012.

The committee also appreciates the contributions of the following personel from FEV, Inc., who helped in reviewing the methodology and results of the vehicle analysis: Gary Rogers, Dean Tomazic, and Aaron Birckett.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of the independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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R.R. Stephenson, Independent Consultant.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Elisabeth M. Drake, NAE, Massachusetts Institute of Technology (retired), and Trevor O. Jones, NAE, ElectroSonics Medical. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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[1] National Academy of Engineering.

Contents

APPENDIXES[1]

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[1] Note that Appendixes D through H appear only in the electronic version of this report, available at http://www.nap.edu/catalog.php?record_id=18264.

Select Acronyms and Abbreviations

AEO	*Annual Energy Outlook*
AFV	alternative fuel vehicle
bbl	barrel
bbl/d	barrels per day
BEV	battery electric vehicle
Btu	British thermal unit
CAA	Clean Air Act
CAFE	Corporate Average Fuel Economy
CCS	carbon capture and storage
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CTL	coal to liquid (fuel)
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EOR	enhanced oil recovery
EPAct	Energy Policy Act
ETA	Energy Tax Act
FCEV	hydrogen fuel cell electric vehicle
FFV	flex fuel vehicle
gge	gallon of gasoline equivalent
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GTL	gas to liquid (fuel)
H_2	hydrogen
HEV	hybrid electric vehicle
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IHUF	Indexed Highway User Fee
ILUC	indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
LCA	life-cycle assessment
LCFS	Low Carbon Fuel Standard
LDV	light-duty vehicle
Li-ion	lithium ion
LT	light truck
$MMTCO_2e$	million metric ton(s) of CO_2 equivalent
mpg	miles per gallon
mpgge	miles per gallon of gasoline equivalent
NAAQS	National Ambient Air Quality Standards
NEMS	National Energy Modeling System
NHTSA	National Highway Traffic Safety Administration
NO_x	mono-nitrogen oxides, including nitric oxide (NO) and nitrogen dioxide (NO_2)
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
quad	quadrillion British thermal units (of energy)
RFS	Renewable Fuel Standard
RFS2	Renewable Fuel Standard, as amended by EISA
RIN	Renewable Identification Number
tcf	trillion(s) of standard cubic feet
VMT	vehicle miles traveled

NOTE: A more complete list of acronyms and abbreviations is given in Appendix E of the electronic version of this report, available at http://www.nap.edu/catalog.php?record_id=18264.

Overview

This National Research Council report assesses the potential for reducing petroleum consumption and greenhouse gas (GHG) emissions by the U.S. light-duty vehicle fleet by 80 percent by 2050. It examines the technologies that could contribute significantly to achieving these two goals and the barriers that might hinder their adoption. Four general pathways could contribute to attaining both goals—highly efficient internal combustion engine vehicles and vehicles operating on biofuels, electricity, or hydrogen. Natural gas vehicles could contribute to the additional goal of reducing petroleum consumption by 50 percent by 2030.

Scenarios identifying promising combinations of fuels and vehicles illustrate what policies could be required to meet the goals. Several scenarios are promising, but strong and effective policies emphasizing research and development, subsidies, energy taxes, or regulations will be necessary to overcome cost and consumer choice factors.

All the vehicles considered will be several thousand dollars more expensive than today's conventional vehicles, even by 2050, and near-term costs for battery and fuel cell vehicles will be considerably higher. Driving costs per mile will be lower, especially for vehicles powered by natural gas or electricity, but vehicle cost is likely to be a significant issue for consumers for at least a decade. It is impossible to know which technologies will ultimately succeed, because all involve great uncertainty. It is thus essential that policies be broad, robust, and adaptive.

All the successful scenarios combine highly efficient vehicles with at least one of the other three pathways. Large gains beyond the standards proposed for 2025 are feasible from engine and drivetrain efficiency improvements and load reduction (e.g., weight and rolling resistance). Load reduction will improve the efficiency of all types of vehicles regardless of the fuel used.

If their costs can be reduced and refueling infrastructure created, natural gas vehicles have great potential for reducing petroleum consumption, but their GHG emissions are too high for the 2050 GHG goal.

Drop-in biofuels (direct replacements for gasoline) produced from lignocellulosic biomass could lead to large reductions in both petroleum use and GHG emissions. While they can be introduced without major changes in fuel delivery infrastructure or vehicles, the achievable production levels are uncertain.

Battery costs are projected to drop steeply, but limited range and long recharge time are likely to limit the use of all-electric vehicles mainly to local driving. Advanced battery technologies are under development, but all face serious technical challenges.

Battery and fuel cell vehicles could become less expensive than the advanced internal combustion engine vehicles of 2050. Fuel cell vehicles are not subject to the limitations of battery vehicles, but developing a hydrogen infrastructure in concert with a growing number of fuel cell vehicles will be difficult and expensive.

The GHG benefits of all fuels will depend on their production and use without large net emissions of carbon dioxide. To the extent that fossil resources become a large source of non-carbon transportation fuels (electricity or hydrogen), then the successful implementation of carbon capture and storage will be essential.

Summary

Internal combustion engines operating on petroleum fuels have powered almost all light-duty vehicles (LDVs) for the past century. However, concerns over energy security from petroleum imports and the effect of greenhouse gas (GHG) emissions on global climate are driving interest in alternatives. LDVs account for almost half of the petroleum use in the United States, and about half of that fuel is imported (EIA, 2011). LDVs also account for about 17 percent of the total U.S. GHG emissions (EPA, 2012).

In response to a congressional mandate in the Senate's Fiscal Year 2010 Energy and Water Development Appropriations Bill (Report 111-45) for the U.S. Department of Energy, Energy Efficiency and Renewable Energy (DOE-EERE), the National Research Council (NRC) convened the Committee on Transitions to Alternative Vehicles and Fuels (see Appendix B) to assess the potential for vehicle and fuel technology options to achieve substantial reductions in petroleum use and GHG emissions by 2050 relative to 2005. This report presents the results of that analysis and suggests policies to achieve the desired reductions. The statement of task (see Appendix A) specifically asks how the on-road LDV fleet could reduce, relative to 2005,

- Petroleum use by 50 percent by 2030 and 80 percent by 2050, and
- GHG emissions by 80 percent by 2050.

SCOPE AND APPROACH

Four general pathways could contribute to attaining both goals—highly efficient internal combustion engine vehicles (ICEVs) and vehicles operating on biofuels, electricity, or hydrogen. Natural gas vehicles could contribute to the additional goal of reducing petroleum consumption by 50 percent by 2030.

This study considered the following types of LDVs:

- ICEVs that are much more efficient than those expected to be available by 2025;
- Hybrid electric vehicles (HEVs), such as the Toyota Prius;
- Plug-in hybrid electric vehicles (PHEVs), such as the Chevrolet Volt;
- Battery electric vehicles (BEVs), such as the Nissan Leaf; BEVs and PHEVs are collectively known as plug-in electric vehicles (PEVs);
- Fuel cell electric vehicles (FCEVs), such as the Mercedes F-Cell, scheduled to be introduced about 2014; and
- Compressed natural gas vehicles (CNGVs), such as the Honda Civic Natural Gas.

The non-petroleum-based fuel technologies examined in the study are hydrogen, electricity, biofuels, natural gas, and liquid fuels made from natural gas or coal. For each fuel and vehicle type, the committee determined current capability and then estimated future performance and costs, plus barriers to implementation, including safety and technology development timelines. The report also comments on key federal research and development (R&D) activities applicable to fuel and vehicle technologies.

BEVs, FCEVs, and CNGVs[1] can operate only on their specific fuel, although hydrogen and electricity can be produced from a variety of sources that might or might not involve the control of emissions of carbon dioxide, the main GHG responsible for human-induced climate change. The engines in ICEVs, HEVs, and PHEVs can use fuels produced from petroleum, biomass, natural gas, or coal.

The committee recognizes the great uncertainties regarding future vehicles and fuels, especially costs, timing of technology advances, commercialization of those advances,

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[1] Vehicles that operate on CNG can also be designed as dual-fuel vehicles that can switch to gasoline when CNG is not available, or as hybrid electric vehicles. To keep the analysis manageable, these options are not considered in this report.

and their penetration into the market. As a result, the committee developed a range of estimates for use in this study.

For vehicle technologies, the committee used two sets of assumptions for cost and performance: (1) midrange estimates that are ambitious but reasonable goals in the committee's assessment; and (2) optimistic estimates which are potentially attainable, but will require greater successes in R&D and vehicle design. Both sets are predicated on the assumption that strong and effective policies are implemented to continually increase requirements or incentives (at least through 2050) to ensure that technology gains are focused on reducing petroleum use and GHG emissions.

Alternate assumptions were also developed for fuels to aid in assessing uncertainties. For example, several production processes were considered for hydrogen and biofuels, and both conventional generation and low-GHG-emission scenarios were considered for electricity.

In its assessment of the current state of LDV fuel and vehicle technologies and their projections to 2050, the committee built on earlier studies by the NRC and other organizations as listed in Appendix D. In addition, the committee examined publicly available literature and gathered information through presentations at open meetings. Insofar as possible, the committee assessed the fuels and vehicle technologies on a consistent and integrated basis. Its approach accounted for important effects, including the following:

- Potential projected performance characteristics of specific vehicles and fuel systems,
- Costs of the technologies including economies of scale and learning,
- Technical readiness,
- Barriers to implementation,
- Resource demands, and
- Time and capital investments required to build new fuel and vehicle technology infrastructure.

The committee also considered crosscutting technologies. For vehicles, these included weight reduction and improvements in rolling and aerodynamic resistance; for fuels, carbon capture and storage (CCS). In addition, the analysis took into account sector-wide effects such as consumer preferences and potential changes in vehicle miles traveled (VMT).

The committee then analyzed the impact of the various options. Vehicle performance was projected using a model developed by the committee and its consultants that estimates the impact of reductions in energy losses. Costs were projected for expected technologies relative to a 2010 base vehicle. These analyses and the results are described in Chapter 2. Efficiencies, costs, and performance characteristics were analyzed consistently for all vehicle classes and powertrain options, with the partial exception of travel range. Fuel technologies were analyzed individually using consistent assumptions and cost data across all fuels as shown in Chapter 3.

The vehicle and fuel data were then used to forecast future LDV fleet energy use and GHG emissions using two models described in Chapter 5. VISION was used to assess technology pathways to on-road fleets in 2050 based on inputs from the vehicle and fuel analyses developed in Chapters 2 and 3. LAVE-Trans—a spreadsheet model that takes into account consumer choices (discussed in Chapter 4), which are affected by vehicle and fuel characteristics, costs, and policy incentives—was used to compare different policy-driven scenarios. These scenarios are not intended as predictions of the future but rather to evaluate the relative potential impact on future petroleum use and GHG emissions of technological success and policy options, and the resulting costs and benefits.

By their nature, all models are simplifications and approximations of the real world and will always be constrained by computational limitations, assumptions, and knowledge gaps. All the models' estimations depend critically on assumptions about technologies, economics, and policies and should best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. The LAVE-Trans model in particular uses the committee's assumptions about technological progress over several decades, how people behave, what things cost and what they are worth. It predicts, in a formal relational structure, how the vehicle fleet composition would then evolve and what the impact would be on petroleum use and GHG emissions. Some of the LAVE-Trans results were surprising, but the committee examined them and the model, fixed mistakes, and revised assumptions, until it was satisfied with the robustness of the outputs that resulted from the inputs. Even so, there is considerable uncertainty about the results presented here. Input assumptions are estimates that may prove inaccurate. The model's handling of market relationships may be simplistic. Nevertheless, as described in Chapter 5, the results are robust for a variety of inputs, and, as long as the results are used with an understanding of the models' strengths and weaknesses, they should be valuable assets in thinking about potential policy actions.

The major results of the committee's work are listed below; additional findings and policy options are embedded in individual chapters of the report.

MEETING THE GOALS OF REDUCING PETROLEUM USE AND GHG EMISSIONS

> **Finding: It will be very difficult for the nation to meet the goal of a 50 percent reduction in annual LDV petroleum use by 2030 relative to 2005, but with additional policies, it might achieve a 40 percent reduction.**

Future petroleum use is likely to decline as more efficient vehicles enter the market in response to the Corporate Average Fuel Economy (CAFE) standards and GHG requirements for 2025, more than compensating for the increased number of vehicles on the road and the miles traveled. These vehicles will be mainly ICEVs, with an increasing share of HEVs. In addition, biofuels mandated by the Renewable Fuel Standard (RFS) could displace a significant amount of petroleum fuels by 2030, especially if coupled with advances in processes for producing "drop-in" cellulosic biofuels (direct substitutes for gasoline or diesel fuel).

Additional policy support may be required to promote increased sales of CNGVs, BEVs, and FCEVs. Even then the nation is unlikely to reach a 50 percent reduction in petroleum use by 2030 because very little time remains for achieving the required massive changes in the on-road LDV fleet and/or its fuel supply. Many of the vehicles on the road in 2030 will have been built by 2015, and these will lower the fuel economy of the on-road fleet.

> **Finding: The goal of an 80 percent reduction in LDV petroleum use by 2050 potentially could be met by several combinations of technologies that achieve at least the midrange level of estimated success. Continued improvement in vehicle efficiency, beyond that required by the 2025 CAFE standards, is an important part of each successful combination. In addition, biofuels would have to be expanded greatly or the LDV fleet would have to be composed largely of CNGVs, BEVs and/or FCEVs.**

The committee considers that large reductions in LDV use of petroleum-based fuels are plausible by 2050, possibly even slightly more than the 80 percent target, but achieving reductions of this size will be difficult. A successful transition path to large reductions in petroleum use will require not only long-term rapid progress in vehicle technologies for ICEVs and HEVs, but also increased production and use of biofuels, and/or the successful introduction and large-scale deployment of CNGVs, BEVs with greatly improved batteries, or FCEVs.

Extensive new fuel infrastructure would be needed for FCEVs. CNGVs would require new supply lines in areas where natural gas is unavailable or in limited supply, and many filling stations. The infrastructure needed for BEVs would mostly be charging facilities, since electricity supply is already ubiquitous. The technology advances required do not appear to require unexpected breakthroughs and can produce dramatic advances over time, but they would have to be focused on reducing fuel use rather than allowing increases in performance such as acceleration. Thus, a rigorous policy framework would be needed, more stringent than the 2025 CAFE/GHG or RFS standards. Large capital investments would be required for both the fuel and vehicle manufacturing infrastructure. Further, alternative vehicles and some fuels will be more expensive than the current technology during the transition, so incentives to both manufacturers and consumers may be required for more than a decade to spur purchases of the new technology. Figure S.1 shows potential petroleum use for technology-specific scenarios.

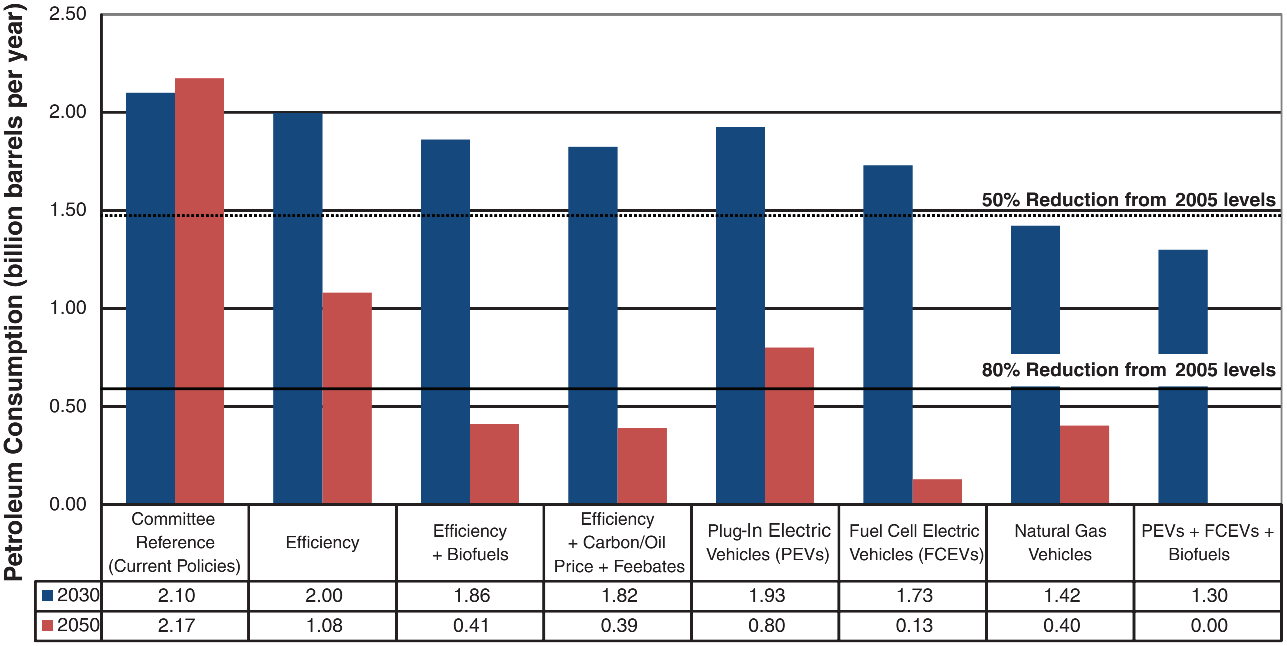
> **Finding: Large reductions are potentially achievable in annual LDV GHG emissions by 2050, on the order of 60 to 70 percent relative to 2005. An 80 percent reduction in LDV GHG emissions by 2050 may be technically achievable, but will be very difficult. Vehicles and fuels in the 2050 time frame would have to include at least two of the four pathways: much higher efficiency than current vehicles, and operation on biofuels, electricity, or hydrogen (all produced with low GHG emissions). All four pathways entail great uncertainties over costs and performance. If BEVs or FCEVs are to be a majority of the 2050 LDV fleet, they would have to be a substantial fraction of new car sales by 2035.**

Achieving large reductions in net GHG emissions from LDVs is more difficult than achieving large reductions in petroleum use. In addition to making all LDVs highly efficient so that their fuel use per mile is greatly reduced, it will be necessary to displace almost all the remaining petroleum-based gasoline and diesel fuel with fuels with low net GHG emissions. This is a massive and expensive transition that, because LDVs emit only about 17 percent of U.S. GHGs, would have to be part of an economy-wide transition to provide major GHG reduction benefits.

The benefits of biofuels depend on how they are produced and on any direct or indirect land-use changes that could lead to GHG emissions. Several studies indicate that sufficient biomass should be available to make a large contribution to meeting the goals of this study, but the long-term costs and resource base for biofuels produced with low GHG emissions need to be demonstrated. Hydrogen and electricity must be produced with low-net-GHG emissions, and the costs of large-scale production are uncertain. Achieving the goals does not require fundamental breakthroughs in batteries, fuel cell systems, or lightweight materials, but significant continuing R&D yielding sustained progress in cost reduction and performance improvement (e.g., durability) is essential.

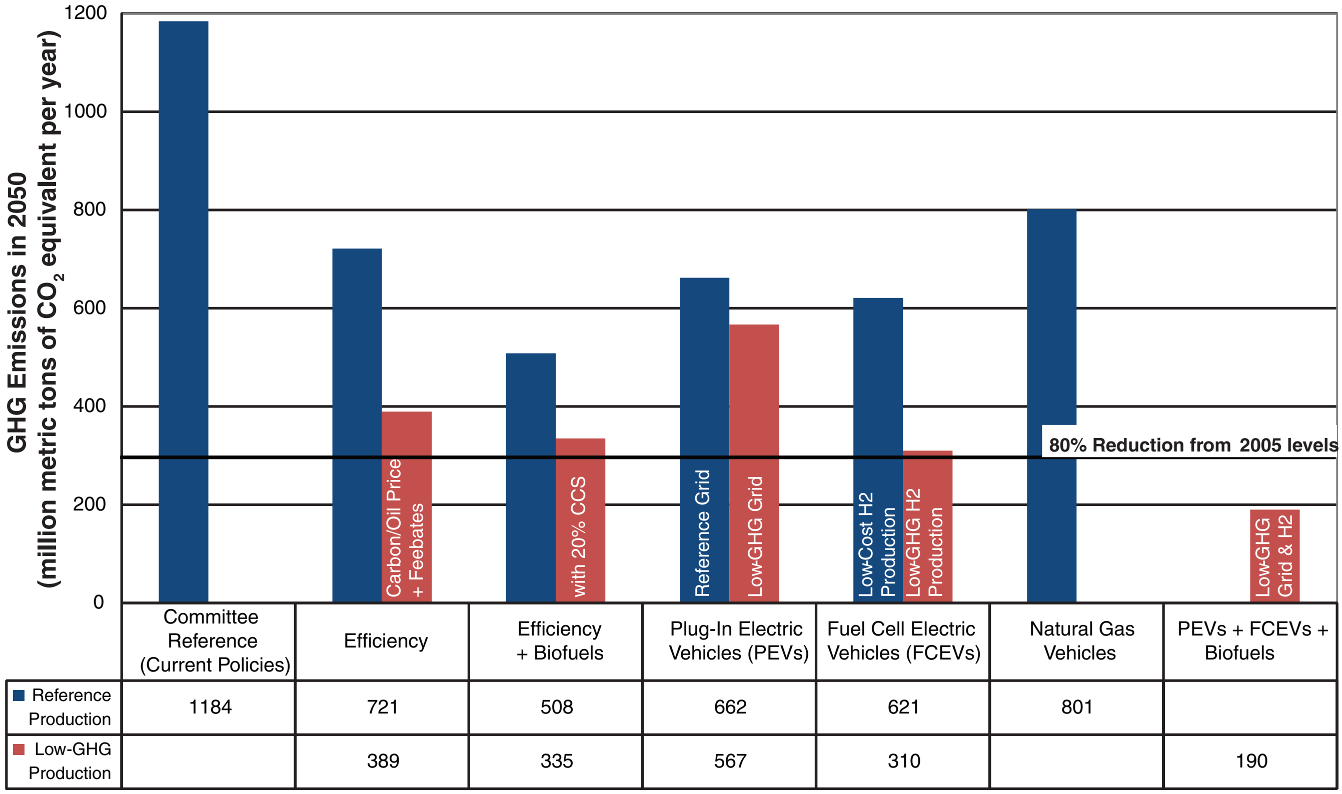
Overall, the committee concluded that LDV GHG emissions could be reduced by some 60 percent to somewhat more than 80 percent by 2050 as shown in Figure S.2. The cost will be greater than that for meeting the 80 percent petroleum reduction goal because options such as CNGVs, or BEVs operating on electricity produced without constraints on GHG emissions, cannot play a large role.

> **Finding: None of the four pathways by itself is projected to be able to achieve sufficiently high reductions in LDV GHG emissions to meet the 2050 goal. Further, the cost, potential rate of implementation of each technology, and response of consumers and**



	Committee Reference (Current Policies)	Efficiency	Efficiency + Biofuels	Efficiency + Carbon/Oil Price + Feebates	Plug-In Electric Vehicles (PEVs)	Fuel Cell Electric Vehicles (FCEVs)	Natural Gas Vehicles	PEVs + FCEVs + Biofuels
🟦 2030	2.10	2.00	1.86	1.82	1.93	1.73	1.42	1.30
🟥 2050	2.17	1.08	0.41	0.39	0.80	0.13	0.40	0.00

FIGURE S.1 Estimated U.S. LDV petroleum use in 2030 and 2050 under policies emphasizing specific technologies. Midrange values are the committee's best estimate of the progress of the technology if it is pursued vigorously. All scenarios except the Committee Reference Case (current policies, including the fuel economy standards for 2025) include midrange efficiency improvements. Controls for GHG emissions from hydrogen and electricity production are not assumed because the main objective is to reduce petroleum use.



	Committee Reference (Current Policies)	Efficiency	Efficiency + Biofuels	Plug-In Electric Vehicles (PEVs)	Fuel Cell Electric Vehicles (FCEVs)	Natural Gas Vehicles	PEVs + FCEVs + Biofuels
🟦 Reference Production	1184	721	508	662	621	801	
🟥 Low-GHG Production		389	335	567	310		190

FIGURE S.2 Estimated U.S. LDV GHG emissions in 2050 under policies emphasizing specific technologies. All scenarios except the Committee Reference Case (current policies, including the fuel economy standards for 2025) include midrange efficiency improvements. Fuel production for these scenarios is assumed to be constrained by policies controlling GHG emissions (low GHG production).

manufacturers to policies are uncertain. Therefore, an adaptive framework that modifies policies as technologies develop and as conditions change is needed to efficiently move toward the long-term policy goals.

Continued improvements in vehicle efficiency, especially load reduction (e.g., through the use of light weight but strong materials), are essential to achieving high GHG reductions and are included in all scenarios as a key step in improving the feasibility of all the other pathways. In addition, some combination of biofuels, BEVs, and FCEVs (with the last two operating on low-GHG electricity or hydrogen) must play a large role. Given the uncertainties surrounding all four of these pathways, there is no single, clearly supported choice of vehicle and fuel system that will lead to 80 percent reduction in GHG emissions.

Much more efficient or alternative vehicles are currently more costly than today's ICEVs and their prices are projected to remain high until the newer technologies are more mature. Achieving an extensive transition by 2050 will thus require government action. These transition costs are in addition to those associated with bringing the technologies to readiness and providing needed infrastructure.

Displacing the incumbent ICEVs and petroleum-based fuels will be difficult. Technologies may not be as successful as anticipated, and the policies to encourage them may not be as successful as modeled by the committee. Furthermore the costs would likely be very large early on, with benefits occurring much later in time. It is essential, then, to ensure that policies, especially those that focus on investment in particular technologies, are not introduced too early (for example, before those new fuel and vehicle technologies are close to market readiness, taking into account the best available information on consumer behavior) or too late (for example, not allowing for the benefits of learning to be realized and to contribute to meeting the goals). Further, it is essential that policies are designed so that they can be adapted to changing evidence about technology and market acceptance, and to market conditions.

In pursuing these goals, costs and benefits of the intended action should both be assessed. Action should be undertaken only upon a reasoned determination that the benefits of intended proposed regulation justify its costs. Scenario analysis has identified strong tipping points for the transition to new vehicle technologies. If policies are insufficient to overcome the early cost differentials, then the transition to such technologies will not occur, and the costs will have been largely wasted.

Finding: Substantial progress toward the goals of reducing LDV petroleum use and GHG emissions is unlikely unless these goals are set and pushed on a nationwide basis through strong and effective policy intervention by the federal government.

All four transition paths are based on technology options that are currently more expensive than their ICEV equivalent, and some will require substantial infrastructure changes and possibly consumer adaptation. Thus, success will depend on consistent and sustained policies that support reduced petroleum use and GHG emissions.

Finding: Even if the nation falls short of the 2050 goals, there are likely to be environmental, economic and national security benefits resulting from the petroleum use and GHG emissions reductions that are achieved.

Finding: The CAFE standard has been effective in reducing vehicle energy intensity, and further reductions can be realized through even higher standards if combined with policies to ensure that they can be achieved.

Policy Option: The committee suggests that LDV fuel economy and GHG emission standards continue to be strengthened to play a significant role after model year 2025 as part of this country's efforts to improve LDV fuel economy and reduce GHG emissions.

Finding: "Feebates," rebates to purchasers of high-fuel-economy (i.e., miles per gallon [mpg]) vehicles balanced by a tax on low-mpg vehicles is a complementary policy that would assist manufacturers in selling the more-efficient vehicles produced to meet fuel economy standards.

Policy Option: The committee suggests that the U.S. government include "feebates" as part of a policy package to reduce LDV fuel use.

Finding: Several types of policies including a price floor for petroleum-based fuels or taxes on petroleum-based fuels could create a price signal against petroleum demand, assure producers and distributors that there is a profitable market for alternative fuels, and encourage consumers to reduce their use of petroleum-based fuels. High fuel prices, whether due to market dynamics or taxes, are effective in reducing fuel use.

The impact of increases in fuel prices, especially on low-income and rural households, could be offset by using the increased revenues from taxes or a price floor for reductions in other taxes. Alternatively, some or all of the revenue generated could be used to replace income lost to the Highway

Trust Fund as gasoline sales decline, so that transport infrastructure could continue to be supported.

> **Finding: Fuel cells, batteries, biofuels, low-GHG production of hydrogen, carbon capture and storage, and vehicle efficiency should all be part of the current R&D strategy. It is unclear which options may emerge as the more promising and cost-effective. At the present time, foreclosing any of the options the committee has analyzed would decrease the chances of achieving the 2050 goals.**

The committee believes that hydrogen/fuel cells are at least as promising as battery electric vehicles in the long term and should be funded accordingly. Both pathways show promise and should continue to receive federal R&D support.

Policy Option: The committee supports consistent R&D to advance technology development and to reduce the costs of alternative fuels and vehicles. The best approach is to promote a portfolio of vehicle and fuel R&D, supported by both government and industry, designed to solve the critical technical challenges in each major candidate pathway. Such primary research efforts need continuing evaluation of progress against performance goals to determine which technologies, fuels, designs, and production methods are emerging as the most promising and cost-effective.

> **Finding: Demonstrations are needed for technologies to reduce GHG emissions at appropriate scale (for example, low-carbon hydrogen and CCS) to validate performance, readiness, and safety. Integrated demonstrations of vehicles and fueling infrastructure for alternative vehicle and fuel systems will be necessary to promote understanding of performance, safety, consumer use of these alternatives, and other important characteristics under real-world driving conditions.**

Policy Option: The committee supports government involvement in limited demonstration projects at appropriate scale and at appropriate times to promote understanding of the performance and safety of alternative vehicles and fueling systems. For such projects, substantial private sector investment should complement the government investment, and the government should ensure that the demonstration incorporates well-designed data collection and analysis to inform future policy making and investment. The information collected with government funds should be made available to the public consistent with applicable rules that protect confidential data.

> **Finding: The commercialization of fuel and vehicle technologies is best left to the private sector in response to performance-based policies, or policies that target reductions in GHG emissions or petroleum use rather than specific technologies. Performance-based policies for deployment (e.g., CAFE standards) or technology mandates (e.g., RFS) do not require direct government expenditure for particular vehicle or fuel technologies. Additional deployment policies such as vehicle or fuel subsidies, or quantity mandates directed at specific technologies are risky but may be necessary to attain large reductions in petroleum use and GHG emissions. For alternative-vehicle and fuel systems, government involvement with industry is likely to be needed to help coordinate commercial deployment of alternative vehicles with the fueling infrastructure for those vehicles.**

Policy Option: The committee suggests that an expert review process independent of the agencies implementing the deployment policies and also independent of any political or economic interest groups advocating for the technologies being evaluated be used to assess available data, and predictions of costs and performance. Such assessments could determine the readiness of technologies to benefit from policy support to help bring them into the market at a volume sufficient to promote economies of scale. If such policies are implemented, there should be specific goals and time horizons for deployment. The review process should include assessments of net reductions in petroleum use and GHG emissions, vehicle and fuel costs, potential penetration rates, and consumer responses.

TECHNOLOGY- AND POLICY-SPECIFIC FINDINGS

Vehicles (Chapter 2)

- Large increases in fuel economy are possible with incremental improvements in currently known technology for both load reduction and drivetrain improvements. The average of all conventional LDVs sold in 2050 might achieve CAFE test values of 74 mpg for the midrange case. Hybrid LDVs might reach 94 mpg by 2050. On-road fuel economy values will be lower.
- To obtain the efficiencies and costs estimated in Chapter 2, manufacturers will need incentives or regulatory standards or both to widely apply the new technologies.
- The unit cost of batteries will decline with increased production and development; in addition, the energy storage (in kilowatt-hours) required for a given vehicle range will decline with vehicle load reduction and improved electrical component efficiency. Therefore, battery pack costs in 2050 for a 100-mile real-world

travel range are expected to drop by a factor of about 5. However, even these costs are unlikely to create a mass market for BEVs, because a battery large enough for a 300-mile real-world range would still present significant weight and volume penalties and probably could not be recharged in much less than 30 minutes. Therefore, BEVs may be used mainly for local travel rather than as all-purpose vehicles.

- BEVs and PHEVs are likely to use lithium-ion batteries for the foreseeable future. Several advanced battery technologies (e.g., lithium-air) are being developed that would address some of the drawbacks of lithium-ion batteries, but their potential for commercialization by 2050 is highly uncertain, and they may have their own disadvantages.
- PHEVs offer substantial amounts of electric-only driving while avoiding the range and recharge-time limitations of BEVs. However, their larger battery will always entail a significant cost premium over similar HEVs, and their incremental fuel savings will decrease as the efficiency of HEVs improves.
- The technical hurdles that must be surmounted to develop an all-purpose vehicle acceptable to consumers appear lower for FCEVs than for BEVs. However, the infrastructure and policy barriers appear larger. Well before 2050 the cost of FCEVs could actually be lower than the cost of an equivalent ICEV, and operating costs should also be lower. FCEVs are expected to be equivalent in range and refueling time to ICEVs.
- If CNGVs can be made competitive (with respect to both vehicle cost and refueling opportunities), they will offer a quick and economical way to reduce petroleum use, but as shown in Figure S.2, the reductions in GHG emissions are insufficient for CNGVs to be a large part of a fleet that meets the 2050 GHG goal.
- Although fundamental technology breakthroughs are not essential to reach the mpg, performance, and cost estimates in Chapter 2, new technology developments would substantially reduce the development cost and lead time. In particular, continued research to reduce the costs of advanced materials and battery concepts will be critical to the success of electric vehicles.

Fuels (Chapter 3)

- Meeting the GHG and petroleum reduction goals requires a massive restructuring of the fuel mix used for transportation. The use of petroleum must be greatly reduced, implying retirement of crude oil production and distribution infrastructure. Depending on the progress in drop-in biofuels versus non-liquid fuels, refineries, pipelines, and filling stations might also become obsolete. For BEVs to operate with low GHG emissions, coal- and natural gas-fired electricity generation might have to be greatly reduced unless CCS proves cost-effective. Reliance on natural gas or hydrogen for transportation would require additional infrastructure. With currently envisioned technology, sufficient biofuels could be produced by 2050 to meet the goal of 80 percent reduction in petroleum use if the committee's vehicle efficiency estimates are attained.
- With increasing economic natural gas reserves and growing domestic natural gas production mostly from shale gas, there is enough domestic natural gas to greatly increase its use for the transportation sector without significantly affecting the traditional natural gas markets. Currently the cost of natural gas is very low ($2.5 to $3.5/million Btu) and could remain low for several decades. Environmental issues associated with shale gas extraction (fracking) must be resolved, including leakage of natural gas, itself a powerful GHG, and potential contamination of groundwater. There are several opportunities, direct and indirect, to use natural gas in LDVs, including producing electricity for PEVs and producing hydrogen for FCEVs. The fastest way to reduce petroleum use is probably by direct combustion in CNGVs coupled with efficiency improvements, but that approach is likely to interfere with achieving the GHG goal in 2050.
- Making hydrogen from fossil fuels, especially natural gas, is a low-cost option for meeting future demand from FCEVs, but such methods, by themselves, will not reduce GHG emissions enough to meet the 2050 goal. Making hydrogen with low GHG emissions is more costly (e.g., renewable electricity electrolysis) or requires new production methods (e.g., photoelectrochemical, nuclear cycles, and biological methods) or CCS to manage emissions. Continued R&D is needed on low-GHG hydrogen production methods and CCS to demonstrate that large amounts of low-cost and low-GHG hydrogen can be produced.
- Natural gas and coal conversion to liquid fuel (GTL, CTL) can be used as a direct replacement for petroleum gasoline, but the GHG emissions from these fuels are slightly greater than those from petroleum-based fuels even when CCS is employed at the production plant. Therefore, these fuels will play a small role in reducing petroleum use if GHG emissions are to be reduced simultaneously.
- Carbon capture and sequestration is a key technology for meeting the 2050 goal for GHG emissions reductions. Insofar as fossil fuels are used as a source of electricity or hydrogen to power LDVs, CCS will

be essential. The only alternatives are nuclear power and renewable energy sources, including biofuels. Applying CCS to biofuel production could result in slightly negative net emissions.

Consumer Barriers (Chapter 4)

- Widespread consumer acceptance of alternative vehicles and fuels faces significant barriers, including the high initial purchase cost of the vehicles and the perception that such vehicles offer less utility and convenience than conventional ICEVs. Overcoming these barriers is likely to require significant government policy intervention that could include subsidies and vigorous public information programs aimed at improving consumers' familiarity with and understanding of the new fuels and powertrains. Consumers are used to personal vehicles that come in a wide variety of sizes, styles, and prices that can meet most needs ranging from basic transportation to significant cargo hauling. Conventional ICEVs can be rapidly refueled by a plentiful supply of retailers, effectively giving the vehicles unlimited range. Conversely, in the early years, alternative vehicles will likely be limited to a few body styles and sizes and will cost from a few hundred to many thousands of dollars more than their conventional ICEV counterparts. Some will rely on fuels that are not readily available or have limited travel range, or require bulky energy storage that will limit their cargo and passenger capacity.

Additional Findings from Policy Modeling (Chapter 5)

- Including the social costs of GHG emissions and petroleum dependence in the cost of fuels (e.g., via a carbon tax) provides important signals to the market that will promote technological development and behavioral changes. Yet these pricing strategies alone are likely to be insufficient to induce a major transition to alternative, net-low-carbon vehicle technologies and/or energy sources. Additional strong, temporary policies may be required to break the "lock-in" of conventional technology and overcome the market barriers to alternative vehicles and fuels.
- If two or more of the fuel and/or vehicle pathways identified above evolve through policy and technology development as shown in a number of the committee's scenarios, the committee's model calculations indicate benefits of making a transition to a low-petroleum, low-GHG energy system for LDVs that exceed the costs by a wide margin. Benefits include energy cost savings, improved vehicle technologies, and reductions in petroleum use and GHG emissions. Costs refer to the additional costs of the transition over and above what the market is willing to do voluntarily. However, as noted above, modeling results should be viewed as approximations at best because there is by necessity in such predictions a great deal of uncertainty in estimates of both benefits and costs. Furthermore, the costs are likely to be very large early on with benefits occurring much later in time.
- It is essential to ensure that policies, especially those that focus on investment in particular technologies, are not introduced before those new fuel and vehicle technologies are close to market readiness and consumer behavior toward them is well understood. Forcing a technology into the market before it is ready can be costly. Conversely, neglecting a rapidly developing technology could lead to forgone significant benefits. Policies should be designed to be adaptable so that mid-course corrections can be made as knowledge is gained about the progress of vehicle and fuels technologies. Further, it is essential that policies be designed so that they can be adapted to changing evidence about technology and market acceptance, and market conditions.
- Depending on the readiness of technology and the timing of policy initiatives, subsidies or regulations for new-vehicle energy efficiency and the provision of energy infrastructure may be required, especially in the case of a transition to a new vehicle and fuel system. In such cases, policy support might be required for as long as 20 years if technological progress is slow (e.g., BEVs with lithium-ion batteries may require 20 years of subsidies to achieve a large market share).
- Advance placement of refueling infrastructure is critical to the market acceptance of FCEVs and CNGVs. It is likely to be less critical to the market acceptance of grid-connected vehicles, since many consumers will have the option of home recharging. However, the absence of an outside-the-home refueling infrastructure for grid-connected vehicles is likely to depress demand for these vehicles. Fewer infrastructure changes will be needed if the most cost-effective solution evolves in the direction of more efficient ICEVs and HEVs combined with drop-in low-carbon biofuels.
- Research is needed to better understand key factors for transitions to new vehicle fuel systems such as the costs of limited fuel availability, the disutility of vehicles with short ranges and long recharge times, the numbers of innovators and early adopters among the car-buying public, as well as their willingness to pay for novel technologies and the risk aversion of the majority, and much more. More information is also needed on the transition costs and barriers to

production of alternative drop-in fuels, especially on the type of incentives necessary for low-carbon biofuels. The models this committee and others have used to analyze the transition to alternative vehicles and/or fuels are first-generation efforts, more useful for understanding processes and their interactions than for producing definitive results.

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1

Introduction

Internal combustion engines (ICEs) operating on petroleum fuels have powered almost all light-duty vehicles (LDVs) for a century. The dominance of ICEs over steam and batteries has been due to their low cost, high power output, readily available fuel, and ability to operate for long distances in a wide range of temperatures and environmental conditions. Although ICEs can run on many fuels, gasoline and diesel have remained the fuels of choice because of their low cost and high energy density, allowing hundreds of miles of driving before refueling. Crude oil has remained the feedstock of choice for these fuels because production has kept pace with demand and world reserves have actually been expanded as a result of ongoing technological progress. The co-evolution and co-optimization of ICE and petroleum-based fuel technology, infrastructure, and markets have proven resilient to challenges from market forces such as oil price spikes in a geopolitically complex world oil market as well as environmental policies such as tailpipe pollution reduction requirements.

For nearly 40 years, energy security concerns have motivated efforts to reduce the use of petroleum-based fuels. LDVs consume about half the petroleum used in the United States, and about half is imported, tying Americans to a world oil market that is vulnerable to supply disruptions and price spikes and contributing about $300 billion to the nation's trade deficit (EIA, 2011).

More recently, concerns have been growing over emissions of carbon dioxide (CO_2), the most important of the greenhouse gases (GHGs) that threaten to cause serious problems associated with global climate change.[1] Petroleum use is the largest source of GHG emissions in the United States. Because LDVs account for the single largest share of U.S. petroleum demand and directly account for 17 percent of total U.S. GHG emissions (EPA, 2012), they have become the subject of policies for mitigating climate change.

For these reasons, U.S. policy makers seek to both improve the fuel efficiency of LDVs and promote the development and adoption of alternative fuels and vehicles (AFVs). Here "alternative fuels" refers to non-petroleum-based fuels, including plant-based fuels that are otherwise essentially identical to gasoline or diesel fuel, and to powertrains much more efficient than today's or capable of using alternative fuels, including non-liquid energy carriers such as natural gas, hydrogen, and electricity. Numerous studies have addressed these issues over the years, reflecting the interest in these goals. Substantial but uneven progress has been made on LDV efficiency, and a small but significant penetration of hybrid electric vehicles in the marketplace has contributed to this goal. Otherwise little progress has been made on AFVs in the marketplace beyond the quantities of ethanol still used almost exclusively in gasoline blends.

Since its beginnings over 100 years ago, the automotive sector has succeeded through a combination of private market forces and public policies. The energy use and GHG emissions challenges with which we now are grappling are the unintended and largely unforeseen by-products of that success.

This report is the result of a study by a committee appointed to evaluate and compare various approaches to greatly reducing the use of oil in the light-duty fleet and GHG emissions from the fleet. As specified in the statement of task (Appendix A), the Committee on Transitions to Alternative Vehicles and Fuels was charged with assessing the status of and prospects for technologies for LDVs and their fuels, and with estimating how the nation could meet one or both of two goals:

1. Reduce LDV use of petroleum-based fuels by 50 percent by 2030 and 80 percent by 2050.
2. Reduce LDV emissions of GHGs by 80 percent by 2050 relative to 2005.

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[1] As used in this report, GHG means the total of all greenhouse gases, as converted to a common base of global warming potential, i.e., CO_2 equivalent (CO_2e). For tail pipe emissions, CO_2 is used.

The 2050 petroleum reduction goal is easier to meet than the 2050 GHG goal because more options can be employed. In fact, reducing GHGs by 80 percent is likely to require reducing petroleum use by at least 80 percent. Petroleum use by the light duty fleet was 125 billion gallons gasoline in 2005 (EIA, 2011), so the targets are 62.5 billion gallons in 2030 and 25 billion in 2050.

GHG emissions from the LDV fleet in 2005 were 1,514 million metric tons of CO_2 equivalent ($MMTCO_2e$) on a well-to-wheels basis (EPA, 2012). An 80 percent reduction from that level means that whatever fleet is on the road in 2050 can be responsible for only 303 $MMTCO_2e$/year. That is the budget within which the fleet must operate to meet the goal.

Achieving an 80 percent reduction in LDV-related emissions is only possible with a very high degree of net GHG reduction in whatever energy supply sectors are used to provide fuel for the vehicles. In short, it is not possible to greatly "de-carbonize" LDVs without greatly de-carbonizing the major energy supply sectors of the economy.

The committee determined potential costs and performance levels for the vehicle and fuel options. Because of the great uncertainty in estimating vehicle cost and performance in 2050, the committee considered two levels, midrange and optimistic. Midrange goals for cost and performance are ambitious but plausible in the committee's opinion. Meeting this level will require successful research and development and no insurmountable barriers, such as reliance on critical materials that may not be available in sufficient quantities. The more optimistic goals are stretch goals: possible without fundamental technology breakthroughs, but requiring greater R&D and vehicle design success. All the vehicle and fuel cost and performance levels are based on what is achievable for the technology.

Other factors also will be very important in determining what is actually achieved. In particular, government policy will be necessary to help some new and initially costly technologies into the market, consumer attitudes will be critical in determining what technologies are successful, and of course, the price and availability of gasoline will be important in determining the competitiveness of alternative vehicles and fuels.

1.1 APPROACH AND CONTENT

To analyze all these issues, the committee constructed and analyzed various scenarios, combining options under the midrange and optimistic cost and performance levels to see

BOX 1.1
Analytical Techniques Used in This Report

The committee relied on four models to help form its estimates of future vehicle characteristics, their penetration into the market, and the impact on petroleum consumption and GHG emissions. Chapter 2 and Appendix F describe two of the models. One is an ICEV model developed by a consultant that projects vehicle efficiency out to 2050 by focusing on reduction of energy losses, rather than the usual technique of adding efficiency technologies until the desired level is reached. The committee's approach avoids the highly uncertain predictions of which technologies will be employed several decades from now and ensures that efficiency projections are physically achievable and that synergies between technologies are appropriately accounted for. The second is a spreadsheet model of technology costs developed by the committee, which focused on applying consistent assumptions across all of the different powertrain types. The analytical approach for both models is fully documented and the data are available in Appendix F. The methodology and results for both of these models were intensively reviewed by the committee, the committee staff, another consultant, and experts from FEV, Inc., an engineering services company. Reviewers of this report were also selected for their ability to understand this approach, which they endorsed.

The VISION and LAVE-Trans models are described in Chapter 5 and Appendix H. VISION is a standard model for analyzing transportation scenarios for fuel use and emissions. It is freely available through the U.S. Department of Energy. The committee modified it for consistency with the committee's assumptions such as on vehicle efficiencies and usage and fuel availability. The committee carefully monitored the modifications and reviewed the results, which are consistent with other analyses.

LAVE-Trans is a new model developed by a committee member for an analysis of California's energy future and expanded to the entire nation by the committee. It is unique among models in that it explicitly addresses market responses to factors such as vehicle cost and range, aversion to new technology, and fuel availability. It analyzes the effectiveness of policies in light of these market responses. The committee and staff spent considerable time reviewing LAVE-Trans and its results. In addition to presentations and discussions at committee meetings, one committee member and the study director spent a day going over the model with the developer and his associates. Another committee member examined intermediate calculations as well as model outputs. The results were also compared to VISION results for identical inputs and assumptions. These examinations led to recalibrations and changes in model assumptions. Reviewers of this report were also selected for their ability to understand the model, and they confirmed its validity.

how the petroleum and GHG reduction goals could be met. It also explored how consumers might react to new technologies. Then the committee compared the technological and economic feasibility of meeting the goals using the available options, the environmental impacts of implementing them, and changes in behavior that might be required of drivers to accommodate new technologies. Finally, the committee examined the policies that might be necessary to implement the scenarios.

Vehicle options are explored in Chapter 2 and fuels in Chapter 3. Chapter 4 discusses factors that will affect consumer choices in considering which vehicles to purchase, and Chapter 5 describes how the scenario modeling was done and the results. Box 1.1 briefly describes the models used in Chapters 2 and 5 and how they were validated.

Chapter 6 discusses policies that could enable the various options and encourage their penetration into the market as needed to implement the scenarios. Finally, Chapter 7 discusses the committee's suggested policy options that are drawn from Chapter 6. Several current policies are encouraging actions that will reduce GHG emissions and petroleum use. The Corporate Average Fleet Economy (CAFE) standards require vehicle manufacturers to sell efficient vehicles. The Renewable Fuel Standards mandate the use of biofuels. Box 1.2 briefly describes these policies. In addition, tax credits for battery vehicles encourage consumers to buy them. Fuel taxes, carbon reduction measures such as carbon taxes, and other standards and subsidies also could be used. State and local policies may also be important, particularly in the absence of activist federal policies, but the focus of

BOX 1.2
U.S. Policies Directly Affecting Fuel Consumption

U.S. Corporate Average Fuel Economy (CAFE) Standards

From the mid-1970s through 2010, the United States had one set of standards that applied to passenger cars and another set that applied to light-duty trucks. These standards were administered by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation, following requirements in legislation passed by the U.S. Congress in 1975. They first became effective in the 1978 model year. The standard for passenger cars that year was 18.0 miles per gallon (mpg). The standard increased to 27.5 mpg for the 1985 model year and varied between that level and 26.0 mpg from model year 1986 through model year 1989. In model year 1990 it was raised again to 27.5 mpg and remained at that level through model year 2010. The first combined light truck standard applied to model year 1985 vehicles and was set at 19.5 mpg. The light truck standard ranged between 20.0 and 20.7 mpg between model years 1986 and 1996, remained at 20.7 mpg for model years 1996 through 2004, and increased to 23.5 mpg by model year 2010.

More recently, the federal government implemented two new sets of standards. In 2010, complementary standards were set by the Environmental Protection Agency (EPA) based on greenhouse gas (GHG) emissions and by NHTSA based on fuel economy. NHTSA's CAFE standard for 2016 was set at 34.1 mpg for cars and light trucks. In 2012, new standards were set by EPA and NHTSA through 2025, although the NHTSA standards for 2022-2025 are proposed and not yet final, pending a midterm review. NHTSA's CAFE standard for 2025 is 48.7-49.7 mpg. If flexibilities for paying fines instead of complying, flexible fuel vehicle (FFV) credits, electric vehicle credits, and carryforward/carryback provisions are considered, NHTSA estimated that the CAFE level would be 46.2-47.4 mpg. This does not consider off-cycle credits, which could further reduce the test cycle results by up to 2-3 mpg. Thus, for comparison purposes, the committee used 46 mpg as the tailpipe mpg levels comparable to the committee's technology analyses in Figure 2.1. Also note that on-road fuel economy will be significantly lower—the committee used a discount factor of 17 percent in assessing in-use benefits in Chapter 5. The standards are discussed in more detail in Chapter 5. In particular, see Box 5.1.

Renewable Fuel Standard

The federal Renewable Fuel Standard (RFS) was created under the Energy Policy Act of 2005 because Congress recognized "the need for a diversified portfolio of substantially increased quantities of . . . transportation fuels" to enhance energy independence (P.L. 109-58). The RFS was amended by the Energy Independence and Security Act (EISA) of 2007 which created what is referred to as RFS2. RFS2 mandates volumes of four categories of renewable fuels to be consumed in U.S. transportation from 2008 to 2022. The four categories are:

- Conventional biofuels—15 billion gallons/year of ethanol derived from corn grain or other biofuels.
- Biomass-based diesel—currently 1 billion gallons/year are required.
- Advanced biofuels from cellulose or certain other feedstocks that can achieve a life-cycle GHG reduction of at least 50 percent.
- Cellulosic biofuels, which are renewable fuels derived from any cellulose, hemicellulose, or lignin from renewable biomass and that can achieve a life-cycle GHG reduction threshold of at least 60 percent. In general, cellulosic biofuels also qualify as renewable fuels and advanced biofuels.

this report is on actions the federal government can take. Chapters 6 and 7 estimate the relative effectiveness of U.S. policies in achieving the goals of this study.

The vehicle and fuel options discussed in this report generally are more expensive and/or less convenient for consumers than those that are available now. The societal benefits they provide (in particular, lower oil consumption and GHG emissions) will not, by themselves, be sufficient to ensure rapid penetration of the new technologies into the market. Therefore strong and effective policies will be necessary to meet the goals of this study. By "strong public policies," the committee means options such as steadily increasing fuel standards beyond those scheduled for 2025, measures to substantially limit the net GHG emissions associated with the production and consumption of LDV fuels, and large-scale support for electric vehicles or fuel cell vehicles to help them overcome their high initial cost and other consumer concerns. It also may be necessary to have policies that ensure that the fuels required by alternative powertrains are readily available.

Although the committee is generally skeptical of the value of the government picking winners and losers, the goal of drastically reducing oil use inherently entails a premise of picking a loser (oil) and developing (and perhaps promoting) winners among a set of vehicles and fuel resources.

In turn, implementation of such policies is likely to depend on a strong national imperative to reduce oil use and GHG emissions. The committee has not studied such an imperative but notes that, given the length of time needed to make major changes in the nation's light-duty vehicle fleet, additional policies will be needed soon to meet the goals.

1.2 REFERENCES

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2

Alternative Vehicle Technologies: Status, Potential, and Barriers

2.1 INTRODUCTION AND OVERALL FRAMEWORK FOR ANALYSES

Virtually all light-duty vehicles on U.S. roads today have internal combustion engines (ICEs) that operate on gasoline (generally mixed with about 10 percent ethanol produced from corn) or diesel fuel. To achieve very large reductions in gasoline use and greenhouse gas emissions from the light-duty fleet, vehicles in 2050 must be far more efficient than now, and/or operate on fuels that are, on net, not based on petroleum and are much less carbon-intensive. Such fuels include some biofuels, electricity, and hydrogen. This chapter describes the vehicle technologies that could contribute to those reductions and estimates how their costs and performance may evolve over coming decades. Chapter 3 considers the production and distribution of fuels and their emissions.

Improving the efficiency of conventional vehicles, including hybrid electric vehicles (HEVs), is discussed first.[1] It is, up to a point, the most economical and easiest-to-implement approach to saving fuel and reducing emissions. It includes reductions of the loads the engine must overcome, specifically vehicle weight, aerodynamic resistance, rolling resistance, and accessories, plus improvements to the ICE powertrain and HEV electric systems However, if improved efficiency was the only way to meet the goals, then, for the expected vehicle miles traveled (VMT) in 2050, the average on-road fleet fuel economy would have to exceed 180 mpg.[2] Since that is extremely unlikely, at least with currently identifiable technologies, additional options will be needed. Options considered by the committee include biofuels (discussed in Chapter 3), plug-in hybrid electric vehicles (PHEVs), battery-electric vehicles (BEVs [PHEVs and BEVs are collectively referred to as plug-in vehicles, PEVs]), fuel cell electric vehicles (FCEVs), and ICE vehicles (ICEVs) using compressed natural gas (CNGVs).

ICEVs and PHEVs will require little or no modification to operate on "drop-in" biofuels or synthetic gasoline derived from natural gas or coal. Vehicles that are powered by electricity or hydrogen are very different from current vehicles as described later in this chapter. CNGVs are also discussed, as they require a much larger fuel tank and other modifications. Upstream impacts of producing and providing electricity, hydrogen, and CNG are discussed in Chapter 3.

All these alternative vehicle options currently are more expensive than conventional ICEVs. The rate at which research and development (R&D) improves the performance and reduces the cost of new technologies is highly uncertain. To address this uncertainty, the analysis in this chapter considers two technology success pathways. The midrange case is the committee's best assessment of potential cost and performance should all technologies be pursued vigorously. The committee also developed a stretch case with more optimistic, but still feasible, assumptions about advances in technology and low-cost manufacturing. Details of the technology assessments are in Appendix F.

The committee's estimates are not based on detailed evaluations of all the specific technologies that might be used by 2050. It is impossible to know exactly which technologies will be used that far in the future, especially since major shifts from current technology will be necessary to meet this study's goals for reduced light-duty vehicle (LDV) petroleum

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[1] All fuel economy (mpg) and fuel consumption numbers discussed in Chapter 2 are based on unadjusted city and highway test results or simulations, and do not include in-use efficiency adjustments.

[2] To meet the goal of 303 million metric tons of carbon dioxide equivalent ($MMTCO_2e$), 80 percent reduction from the 1514 light duty fleet emissions in 2005, with gasoline responsible for 10.85 kilograms CO_2e/gallon (8.92 from the tail pipe, the rest from refining and other upstream activities), at most only 28 billion gallons/year could be used (vs. 125 billion now). VMT in 2050 is expected to be about 5 trillion miles (see Chapter 5). Therefore, if the goal were to be met only with efficiency and no advanced vehicle or fuel technology, average economy would have to be 180 mpg. For this case only, the 80 percent oil reduction goal (28 billion gallons) is identical to the GHG goal.

use and GHG emissions.[3] The optimistic and midrange estimates reflect the committee's appraisal of the overall development challenges facing the general pathways, and the promise of the various technologies that might be employed to meet the challenges. These estimates do not consider issues of market acceptance, which are addressed in Chapters 4 and 5, and are not based on specific policies to encourage market acceptance. Both estimates assume that policies are adopted that are sufficiently effective to overcome consumer and infrastructure barriers to adoption.

The committee reviewed a wide range of studies on technology potential and cost but was not able to find a study based on up-to-date technology assumptions and a consistent methodology for all types of technologies through 2050. The 2017-2025 light duty fuel economy standards were based on analyses that included major improvements in data and estimation of technology benefits and costs, but assessed technology only through 2025 (EPA and NHTSA, 2011). The 2009 MultiPath study (ANL, 2009) used a consistent methodology through 2050, but it lacked this recent data. Thus, the committee performed its own assessment of technology effectiveness and costs, as described below and in Appendix F.

In order to compare technologies, all costs discussed in this chapter assume the economies of scale from high volume production even in the early years when production is low. The modeling in Chapter 5, which estimates the actual costs of following specific trajectories, modified these costs for early and low-volume production.

Great care was taken to apply consistent assumptions to all of the technologies considered. For example, the same amount of weight reduction was applied to all vehicle types, and vehicle costs were built up from one vehicle type to the next (e.g., hybrid costs were estimated based on changes from conventional vehicles, and PEV costs were based on changes from hybrid vehicles). This approach does not reduce the large uncertainty in forecasting future benefits and costs, but it does help ensure that the relative differences in costs between different technologies are appropriately assessed and are more accurate than the absolute cost estimates.

The committee made every attempt to ensure accurate technology assumptions. Fundamental limitations for all technologies were considered for all future assessments, such as the ones discussed below for lithium-ion (Li-ion) battery chemistry and for engine losses. As these limits were approached, the rate of technology improvement was slowed down to ensure that the estimates stayed well short of the limits.

On the other hand, learning occurs primarily because manufacturers are very good at coming up with better and more efficient incremental improvements. For example, 10 years ago technology that uses turbochargers to boost exhaust gas recirculation (EGR) was virtually unknown for gasoline engines. This new development, enabled by sophisticated computer simulations and design, has the potential to improve overall ICEV efficiency by about 5 percent. Certainly some of the currently known technologies will not pan out as planned, but it is equally certain that there will be incremental improvements beyond what we can predict now. The estimates in this chapter reflect an effort to strike a careful balance between these considerations.

Learning also applies to cost. Historically, technology costs have continuously declined due to incremental improvements. For example, 6-speed automatic transmissions, currently the most common type, are cheaper to manufacturer than 4-speed automatic transmissions, thanks to innovative power flow designs that allow additional gear combinations with fewer clutches and gearsets.

Although significant continuing R&D yielding sustained progress and cost reduction in all areas is essential, the technology estimates used for the committee's analyses do not depend on any unanticipated and fundamental scientific breakthroughs in batteries, fuel cell systems, lightweight materials, or other technologies. Therefore the estimates for improvements may be more readily attained, especially for 2050, when technology breakthroughs are quite possible. For example:

- Batteries beyond Li-ion were not considered for PEVs because the challenges facing their development make their availability highly speculative.
- Fuel cell efficiency gains were much less than theoretically possible, based on the assumption that developers will consider reducing the cost of producing a given power level to be more important.
- Reducing weight with carbon fiber materials was not included in the analyses, because the committee was uncertain if costs would be low enough by 2050 for mass market acceptance.
- The annual rate of reduction for the various vehicle energy losses was assumed to diminish after 2030, usually to about half of the historical rate of reduction or the rate projected from 2010 to 2030. This reflects reaching the limits of currently known technology and implicitly assumes that the rate of technology improvements will slow in the future, despite the current trend of accelerating technology introduction.
- Only turbocompounding was considered for waste heat recovery, even though other methods with much

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[3] The committee did not assess GHG emissions from the production of vehicles or include such emissions in its analyses of emissions trends later in this report. Given that vehicles are expected to last about 15 years, any differences in production emissions will not make a large difference in lifetime emissions. In addition, data on emissions from the production of vehicles is poor, and estimates for advanced vehicles in several decades will be even more uncertain.

higher potential waste heat recovery rates are being researched (Ricardo, 2012).

- Radical new ICE combustion techniques with potentially higher thermal efficiency were not considered due to uncertainty about cost and durability. In fact, the assumptions for thermal energy in the committee's modeling for the 2030 optimistic and 2050 midrange cases were very similar to the efficiency levels considered achievable by Ford's next generation Eco-Boost engine with "potentially up to 40% brake thermal efficiency . . . at moderate cost" (Automotive Engineering, 2012).

2.2 VEHICLE FUEL ECONOMY AND COST ASSESSMENT METHODOLOGY

2.2.1 Fuel Economy Estimates

This committee's approach to estimating future vehicle fuel economy differs from most projections of future ICE efficiency, which have generally assessed the benefits of specific technologies that can be incorporated in vehicle designs (see Appendix F). Such assessments work well for estimates out 15 to 20 years, but their usefulness for 2050 suffers from two major problems. One is that it is impossible to know what specific technologies will be used in 2050. The traditional approaches taken to assess efficiency, such as PSAT and ADVISOR, depend on having representative engine maps, which do not exist for the engines of 2050. The second is that as vehicles approach the boundaries of ICE efficiency, the synergies, positive and negative, between different technologies become more and more important; that is, when several new technologies are combined, the total effect may be greater or less than the sum of the individual contributions.

The three-step approach used here avoids these problems. First, for ICE and HEV technologies, sophisticated computer simulations conducted by Ricardo were used to establish powertrain efficiencies and losses for the baseline and 2030 midrange cases.[4] These simulations fully accounted for synergies between technologies. Second, the efficiencies and losses of the different powertrain components and categories were determined. Using these categories to extrapolate efficiencies and losses allowed the committee to properly assess synergies through 2050. Third, the estimates of future efficiencies and losses were simultaneously combined with modeling of the energy required to propel the vehicle as loads, such as weight, aerodynamics, and rolling resistance, were reduced. This approach ensures that synergies are properly assessed and that the modeled efficiency results do not violate basic principles.

The committee estimated conventional powertrain improvements using the results of sophisticated simulation modeling conducted by Ricardo (2011). This modeling was used by the U.S. Environmental Protection Agency (EPA) to help set the proposed 2025 light-duty vehicle CO_2 standards. Ricardo conducted simulations on six different vehicles, three cars and three light trucks, which examined drivetrain efficiency (not load reduction) in the 2020-2025 timeframe. The simulations were based on both existing cutting-edge technologies and analyses of technologies at advanced stages of development.

EPA post-analyzed Ricardo's simulation runs and apportioned the losses and efficiencies to six categories—engine thermal efficiency, friction, pumping losses, transmission efficiency, torque converter losses, and accessory losses. The committee used these results as representative of potential new-vehicle fleet average values in 2025 for the optimistic case and in 2030 for the midrange case. The 2050 mid-level and 2050 optimistic vehicles were constructed by assuming that the rates of improvement in key drivetrain efficiencies and vehicle loads would continue, although at a slower rate, based on the availability of numerous developing technologies and limited by the magnitude of the remaining opportunities for improvement.

Baseline inputs for 2010 ICEVs were developed by the committee from energy audit data that corresponded with specific baseline fuel economy. The model calculates changes in mpg based on changes in input assumptions over EPA's test cycles. Additional details of the model are in Appendix F. The results were averaged to one car and one truck for analysis in the scenarios, but the analysis for all six vehicles is in Appendix F.

Starting with the results for ICEVs, the energy audit model was then applied to the other types of vehicles considered in this report for each analysis year and for the midrange and optimistic scenarios. PHEVs were assumed to have fuel economy identical to their corresponding BEVs[5] while in charge-depleting mode (that is, when energy is supplied by the battery) and to HEVs in charge-sustaining mode (when energy is supplied by gasoline or diesel). Natural gas vehicles were assumed to have the same efficiency as other gasoline fueled vehicles.

Care was taken to use consistent assumptions across the different technologies. For example, the same vehicle load reduction assumptions (weight, aero, rolling resistance) were applied to all of the drivetrain technology packages.

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[4] The committee accepts the Ricardo results. However, it should be noted that they are based in part on input data that has not been peer reviewed because it is proprietary.

[5] The BEVs evaluated have a 100 mile range. BEVs with longer range would have substantially heavier battery packs (and supporting structures), adversely affecting vehicle efficiency. PHEVs might have higher electric efficiency than long-range BEVs.

Variables considered by the model (not all variables were used for each technology) were the following:

- Vehicle load reductions:
  —Vehicle weight,
  —Aerodynamic drag,
  —Tire rolling resistance, and
  —Accessory load;
- ICE:
  —Indicated (gross thermal) efficiency,
  —Pumping losses,
  —Engine friction losses,
  —Engine braking losses, and
  —Idle losses;
- Transmission efficiency;
- Torque converter efficiency;
- Electric drivetrain:
  —Battery storage and discharge efficiencies,
  —Electric motor and generator efficiencies, and
  —Charger efficiency (BEV and PHEV only);
- Fuel cell stack efficiency,
  —Also the FCEV battery loop share of non-regenerative tractive energy;
- Fraction of braking energy recovered; and
- Fraction of combustion waste heat energy recovered.

Details of the input assumptions for alternative technologies and of the operation of the model are described in Appendix F.

2.2.2 Vehicle Cost Calculations

Future costs are more difficult to assess than fuel consumption benefits. The committee examined existing cost assessments for consistency and validity. Fully learned out, high-volume production costs were developed as described in this chapter and in Appendix F.

The primary goal was to treat the cost of each technology type as equitably as possible. The vehicle size and utility were the same for all technology types. Range was the same for all vehicles except for BEVs, which were assumed to have a 100 mile real-world range. Care was taken to match the cost assumptions to the efficiency input assumptions. Results from the efficiency model were used to scale the size of the ICE, electric motor, battery, fuel cell, and hydrogen and CNG storage tanks (as applicable). Consistent assumptions of motor and battery costs were used for HEVs, PHEVs, BEVs, and FCVs. Costs were calculated separately for cars and light trucks.

For load reduction, the cost of lightweight materials, aerodynamic improvements, and reductions in tire rolling resistance were assumed to apply equally to all vehicles and technology types.

ICE technology includes a vast array of incremental engine, transmission, and drivetrain improvements. Past experience has shown that initial costs of new technologies can be high, but generally drop dramatically as packages of improvements are fully integrated over time. The incremental cost of other technologies was compared to future ICE costs (FEV, 2012).

For HEVs, costs specific to the hybrid system were added to ICE costs, and credits for smaller engines and components not needed were subtracted to arrive at the hybrid cost increment versus ICE. Similarly, the other vehicle costs were derived from ICEVs by adding and subtracting costs for various components as appropriate. Battery, motor, and power electronics costs were assessed separately for electric drive vehicles.

2.3 LOAD REDUCTION (NON-DRIVETRAIN) TECHNOLOGIES

Many opportunities exist to reduce fuel consumption and CO_2 emissions by reducing vehicle loads, as shown in Table 2.1. The load reduction portion of improved efficiency will benefit all the propulsion options by improving their fuel efficiency, reducing their energy storage requirements, and reducing the power and size of the propulsion system. This is especially important for hydrogen- and electricity-fueled vehicles because battery, fuel cell, and hydrogen storage costs are quite expensive and scale more directly with power or energy requirements than do internal combustion powertrain costs. In particular, load reduction allows a significant reduction in the size and cost of electric vehicle battery packs.

TABLE 2.1 Non-drivetrain Opportunities for Reducing Vehicle Fuel Consumption

Light weighting	Structural materials Component materials Smart design
Rolling resistance	Tire materials and design Tire pressure maintenance Low-drag brakes
Aerodynamics	C_d (drag coefficient) reduction Frontal area reduction
Accessory efficiency	Air conditioning Efficient alternator Efficient lighting Electric power steering Intelligent cooling system

2.3.1 Light Weighting

Reducing vehicle weight is an important means of reducing fuel consumption. The historical engineering rule of thumb, assuming appropriate engine resizing is applied and vehicle performance is held constant, is that a 10 percent weight reduction results in a 6 to 7 percent fuel consumption savings (NHTSA/EPA/CARB, 2010). The committee specifically modeled the impact of weight reduction for each technology type, as this rule of thumb was derived for conventional drivetrain vehicles and other technologies may differ in their response to weight reduction.

A variety of recent studies (see Appendix) have evaluated the weight reduction potential and cost impact for light duty vehicles through material substitution and extensive vehicle redesign. The long-term goal of the U.S. DRIVE Partnership sponsored by the U.S. Department of Energy DOE) is a 50 percent reduction in weight (DOE-EERE, 2012).[6] Lotus Engineering projects a 2020 potential for about a 20 percent weight reduction at zero cost and 40 percent weight reduction potential at a cost of about 3 percent of total vehicle cost, from an aluminum/magnesium intensive design (Lotus Engineering, 2010).

2.3.1.1 Factors That May Affect Mass Reduction Potential

Towing Capacity Mass reduction potential for some light trucks will be constrained by the need to maintain towing capacity, which limits the potential for engine downsizing and requires high structural rigidity. Towing capacity is the only advantage of body-on-frame over unibody construction, thus it was assumed that the historical trend for conversion of minivans and sport utility vehicles (SUVs) from body-on-frame to unibody construction would continue and all vehicles that did not need significant towing capacity would convert to unibody construction. The committee accounted for towing capacity by reducing the weight of body-on-frame trucks (pickups and some SUVs) by only 80 percent of the mass reduction of passenger cars and unibody trucks (minivans and most SUVs). In other words, if a car in 2050 is estimated to be 40 percent lighter, a corresponding mass reduction for a body-on-frame truck would be limited to 32 percent.

Mass Increases Due to Safety Standards Weight associated with increased safety measures is likely to be lower than in the past. The preliminary regulatory impact analysis for the 2025 Corporate Average Fuel Economy (CAFE) standards looked at weight increases for a variety of safety regulations, including proposed rules that would affect vehicles through 2025 and estimated a potential weight increase of 100-120 pounds (EPA and NHTSA, 2011). That is about a 3 percent mass increase, which was factored into the committee's assessment of weight reduction potential.

Mass Increases for Additional Comfort and Accessories Vehicle weight decreased rapidly in the late 1970s and early 1980s because of high fuel prices and implementation of the initial CAFE standards, then increased significantly during the period from the mid 1980s to the mid 2000s when fuel prices fell and fuel economy standards were kept constant (EPA, 2012). Thus, projecting weight trends into the future is very uncertain.[7] Continued weight increases are inconsistent with the assumptions driving this study, i.e., a future that emphasizes improved vehicle efficiency, increased fuel costs, and strong policies to reduce fuel consumption. Not only will manufacturers have strong incentive to reduce weight, but the historical increase in comfort and convenience features is likely to slow and historical increases in weight associated with emission control technology should not continue.[8] The committee estimated that weight increases associated with additional comfort and accessories for the midrange scenarios would be roughly half of the historical annual weight increase during a period of fixed fuel economy standards, or 5 percent by 2030 and 10 percent by 2050. This adjustment was applied after the weight reductions considered here for lightweight materials. The optimistic cases did not include weight increases for additional comfort and accessories.

Mass Reductions Related to Smart Car Technology In the 2050 timeframe, a significant portion of LDVs may include crash avoidance technology and other features of smart car technology. Although it is possible that such features might lead to weight reduction, that is speculative and was not considered. The committee also did not consider driverless (or

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[6] U.S. DRIVE is a government-industry partnership focused on advanced automotive and related energy infrastructure technology R&D. The partnership facilitates pre-competitive technical information to accelerate technical progress on technologies that will benefit the nation. Further information can be found at http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/us_drive_partnership_plan_may2012.pdf.

[7] In addition to weight increases, improvement in powertrain efficiency has been used to increase performance instead of improving fuel economy in the past. The committee concluded that, as for weight discussed above, power is unlikely to grow significantly under the conditions postulated for this study. Past performance increases occurred primarily during periods of little regulatory pressure, and this study assumes that strong regulations or high gasoline prices will be required to reach the levels of fuel economy discussed here. In addition, the average performance level of U.S. vehicles already is high, and many drivers aren't interested in faster acceleration. Finally, the advanced vehicles expected in the future are likely to operate at high efficiency over a broader range than current engines, so high power engines will detract less from fuel economy. Hence the committee decided that performance increases may not happen to a great degree and, if they did, would likely not have a significant impact on fuel economy in the future.

[8] Future emission reductions will be accomplished largely with improved catalysts and better air/fuel ratio control—neither of which will add weight to the vehicle.

autonomous) vehicles because it is not clear what the impact on fuel use may be. While they may lead to smaller cars and mass reduction because of improved safety, and driving a given route may be more efficient with computer controlled acceleration and braking and continuous information on congestion, people may be encouraged to live further away from their workplaces and other destinations because they can use the time in their vehicles more productively. More information on the potential impact of autonomous vehicles is in Appendix F.

2.3.1.2 Safety Implications

Any effects of fleet-wide weight reduction on safety will depend on how the reductions are obtained and on the distribution of weight reduction over different size classes and vehicle types. However, the footprint-based standards implemented in 2005 for light trucks and 2011 for cars eliminate any regulatory incentive to produce smaller vehicles, and there are few indications that substantial weight reduction through the use of lightweight materials and design optimization will have significant adverse net effects on safety (DOT, 2006). Advanced designs that emphasize dispersing crash forces and optimizing crush stroke and energy management can allow weight reduction while maintaining or even improving safety. Advanced materials such as high strength steel, aluminum and polymer-matrix composites (PMC) have significant safety advantages in terms of strength versus weight. The high strength-to-weight ratio of advanced materials allows a vehicle to maintain or even increase the size and strength of critical front and back crumple zones and maintain a manageable deceleration profile without increasing vehicle weight. Finally, given that all light duty vehicles likely will be down-weighted, vehicle to vehicle crash forces should also be mitigated, and vehicle handling may improve because lighter vehicles are more agile, helping to avoid crashes in the first place.

2.3.1.3 Weight Reduction Amount and Cost

Table 2.2 summarizes the weight reductions and costs per pound saved that are used in the committee's scenarios. The table also includes carbon fiber in 2050 for context, even though the committee considers it unlikely that costs will drop sufficiently for widespread use in vehicles and it was not used in the vehicle benefit and cost analyses. As noted above, the midrange case includes some weight growth from additional consumer features.

The costs of weight reduction are ameliorated by the cost *savings* associated with the corresponding secondary weight savings from downsizing chassis, suspension and engine and transmission to account for the reduced structural requirements and reduced drivetrain loads from the reduced mass. Although estimates of the secondary savings vary, they may approach an additional 30 percent of the initial reduction (NRC, 2011).

2.3.2 Reduced Rolling Resistance

Rolling resistance, and the energy required to overcome it, is directly proportional to vehicle mass. The tire rolling resistance coefficient depends on tire design (shape, tread design, and materials) and inflation pressure. Reductions in rolling resistance can occur without adversely affecting wear and traction (Pike Research and ICCT, 2011). The fuel consumption reduction from a 10 percent reduction in rolling resistance for a specific vehicle is about 1 to 2 percent. If in addition the engine is downsized to maintain equal performance, historically fuel consumption was reduced 2.3 percent (NRC, 2006).

In 2005, measured rolling resistance coefficients ranged from 0.00615 to 0.01328 with a mean of 0.0102. The best is 40 percent lower than the mean, equivalent to a fuel consumption reduction of 4 to 8 percent (8 to 12 percent with engine downsizing). Some tire companies have reduced their rolling resistance coefficient by about 2 percent per year for at least 30 years. Vehicle manufacturers have an incentive to provide their cars with low rolling resistance tires to maximize fuel economy during certification. The failure of owners to maintain proper tire pressures and to buy low rolling resistance replacement tires increases in-use fuel consumption.

For this study, scenario projections of reductions in light-duty new-vehicle-fleet rolling resistance for the midrange case average about 16 percent by 2030, resulting in about a

TABLE 2.2 Summary of Weight Reduction and Costs Relative to Base Year 2010

	Cars and Unibody Light Trucks			Body-on-Frame Light Trucks		
Year	Weight Reduction (%)	Cost ($/lb)	Reduction with Weight Growth (%)	Weight Reduction (%)	Cost ($/lb)	Reduction with Weight Growth (%)
2030	25	1.08	Midrange 20 Optimistic 25	20	0.86	Midrange 15 Optimistic 20
2050	40	1.73	Midrange 30 Optimistic 40	32	1.38	Midrange 22 Optimistic 32
2050 carbon fiber	50	6.0	Optimistic 50	40	6.0	Optimistic 40

4 percent decrease in fuel consumption, and about 30 percent in 2050, for about a 7 percent fuel consumption decrease. For the optimistic case, rolling resistance reductions were projected to be about 25 percent in 2030 and 38 percent in 2050.

2.3.3 Improved Aerodynamics

The fraction of the energy delivered by the drive-train to the wheels that goes to overcoming aerodynamic resistance depends strongly on vehicle speed. Unlike rolling resistance, the energy to overcome drag does not depend on vehicle mass. It does depend on the size of the vehicle, as represented by the frontal area, and on how "slippery" the vehicle is designed to be, as represented by the coefficient of drag. For low speed driving, e.g., the EPA city driving cycle, about one-fourth of the energy delivered by the drivetrain goes to overcoming aerodynamic drag; for high speed driving, one-half or more of the energy goes to overcoming drag. Under average driving conditions, a 10 percent reduction in drag resistance will reduce fuel consumption by about 2 percent. Vehicle drag coefficients vary considerably, from 0.195 for the General Motors EV1 to 0.57 for the Hummer 2. The Mercedes E350 Coupe has a drag coefficient of 0.24, the lowest for any current production vehicle (Autobloggreen, 2009). Vehicle drag can be reduced by measures such as more aerodynamic vehicle shapes, smoothing the underbody, wheel covers, active cooling aperture control (radiator shutters), and active ride height reduction.

For this study's scenarios, reduction in new-vehicle-fleet aerodynamic drag resistance for the midrange case is estimated to average about 21 percent (4 percent reduction in fuel consumption) in 2030 and 35 percent (7 percent reduction in fuel consumption) in 2050. For the optimistic case, the aerodynamic drag reductions are estimated to average about 28 percent in 2030 and 41 percent in 2050.

2.3.4 Improved Accessory Efficiency

Accessories currently require about 0.5 horsepower from the engine for most vehicles on the EPA city/highway test cycle. While small, this is a continual load that affects fuel economy. Accessory load reductions were assessed using Ricardo simulation results and the EPA Energy Audit data, as described above. Overall, test cycle accessory loads were reduced about 21-25 percent by 2030 and 25-35 percent by 2050.

2.4 DRIVETRAIN TECHNOLOGIES FOR REDUCING FUEL CONSUMPTION

Currently, conventional gasoline-fueled ICE drivetrains generally convert about 20 percent of the energy in the gasoline into power at the wheels. The engine cannot operate at peak efficiency most of the time. Within the engine, energy is lost as heat to the exhaust or transferred to the cooling system. Moving parts create frictional losses, intake air is throttled (called "pumping" losses), accessories are powered, and the engine remains in operation at idle and during deceleration. In the transmission, multiple moving parts create friction, and pumps and torque converters create hydraulic losses. Also, when the vehicle brakes, much of the potential energy built up during acceleration is lost as heat in the friction brakes. Many or most of these losses and limitations can be reduced substantially by a variety of technological improvements. The technologies discussed below are just a few of the options. More information can be found in Appendix F. Note that biomass-fueled vehicles are being treated as conventionally powered vehicles in this study.

2.4.1 Conventional Internal Combustion Engine Vehicles

2.4.1.1 Gasoline Engine Drivetrains

Engines will improve efficiency in the future by increasing the maximum thermal efficiency and reducing friction and pumping losses. There are multiple technology paths for accomplishing these improvements.

Although the dominant technology used to control fuel flow in gasoline engines currently is port fuel injection, engines with direct injection of fuel into the cylinders have been rapidly entering the U.S. fleet. Gasoline direct injection (GDI, or just DI) systems provide better fuel vaporization, flexibility as to when the fuel is injected (including multiple injections), more stable combustion, and allow higher compression ratios due to intake air charge cooling. Direct injection reduces fuel consumption across the range of engine operations, including high load conditions, and increases low-rpm torque by allowing the intake valve to be open longer. Future GDI systems using spray-guided injection can deliver a stratified charge allowing a lean air/fuel mixture (i.e., excess air) for greater efficiency.

One approach that is rapidly penetrating the market is to combine direct injection with down-sized turbocharged engines. Turbocharging increases the amount of fuel that can be burned in the cylinders, increasing torque and power output and allowing engine downsizing. The degree of turbocharging is enhanced by GDI because of its cooling effect on the intake (air) charge and reduction of early fuel detonation. Further efficiency improvements are available with more sophisticated turbocharging techniques (e.g., dual-stage turbochargers) and combining turbocharging with some combination of variable valve timing, lean-burn, Atkinson cycle, and cooled and boosted EGR.

Ricardo developed engine maps specifically for an EGR DI turbo system, which uses the turbocharger to boost EGR in addition to intake air. This recirculates additional cooled exhaust gas into the cylinder to reduce intake throttling (and pumping losses), increase compression ratio, enable higher boost and further engine downsizing, and reduce combustion temperatures and early fuel detonation (Ricardo, 2011). This engine is projected to have a fuel economy benefit of 20 to 25 percent, compared to the baseline port fuel injected, naturally aspirated engine, by 2020-2025.

Turbocharging with GDI engines is likely to become very common by 2030 because the costs are modest and the fuel economy improvement significant.

Engine friction is an important source of energy losses. Friction reduction can be achieved by both redesign of key engine parts and improvement in lubrication. The major sources of friction in modern engines are the pistons and piston rings, valve train components, crankshaft and crankshaft seals, and the oil pump. Key friction reduction measures include the following (EEA, 2007):

- Low mass pistons and valves,
- Reduced piston ring tension,
- Reduced valve spring tension,
- Surface coatings on the cylinder wall and piston skirt,
- Improved bore/piston diameter tolerances in manufacturing,
- Offset crankshaft for inline engines, and
- Higher-efficiency gear drive oil pumps.

Over the past two and one half decades, engine friction has been reduced by about 1 percent per year (EEA, 2007). Continuing this trend would yield about an 18 percent reduction by 2030, but considerably greater reduction than this should be possible, especially with continued aggressive vehicle efficiency requirements. For example, surface technologies such as diamond-like carbon and nanocomposite coatings can reduce total engine friction by 10 to 50 percent. Laser texturing can etch a microtopography on material surfaces to guide lubricant flow, and combining this texturing with ionic liquids (made up of charged molecules that repel each other) can yield 50 percent or more reductions in friction.

There will also be improvements to transmission efficiency and reductions in torque converter losses. The primary advanced transmissions over the next few decades are expected to be advanced versions of current automatic transmissions, with more efficient launch-assist devices and more gear ratios; and dual-clutch automated manual transmissions (DCTs). Transmissions with 8 and 9 speeds have been introduced into luxury models and some mass market vehicles, replacing baseline 6-speed transmissions. The overdrive ratios in the 8- and 9-speed transmissions allow lower engine revolutions per minute (rpm) at highway speeds, and the higher number of gears allows the engine to operate at higher efficiency across the driving cycle. A 20 to 33 percent reduction in internal losses in automatic transmissions is also possible by 2020-2025 from a combination of advances, including improved finishing and coating of components, better lubrication, improvements in seals and bearings, and better overall design (Ricardo, 2011). Dual clutch transmissions, currently in significant use in Europe, will also improve with the perfection of dry clutches and other improvements, with an additional reduction in internal losses (beyond advanced automatic transmissions) of about 20 percent. Their cost should also be lower than advanced automatic transmissions.

2.4.1.2 Estimation of Future Internal Combustion Engine and Powertrain Efficiency Improvements

As discussed earlier in Chapter 2, the committee estimated conventional powertrain improvements using the results of sophisticated simulation modeling on six different vehicles conducted by Ricardo for baseline (2010) and future (2025) vehicles. EPA post-analyzed Ricardo's simulation runs and apportioned the losses and efficiencies to six categories—engine thermal efficiency, friction, pumping losses, transmission efficiency, torque converter losses, and accessory losses.

The committee directly used EPA's 2025 results for the 2030 midrange case to ensure adequate time for the technologies to fully penetrate the entire fleet. These results were also extrapolated to 2050 by assuming that the percent annual improvements in each of the six categories after 2030 would be at most half the percent annual improvement calculated for 2010 to 2030. Optimistic estimates were calculated the same way, except that the Ricardo runs were used for 2025 instead of delaying the results until 2030. The total reductions for the various vehicles and losses are shown in Tables 2.9, 2.10, and 2.11, and in Appendix F.

2.4.1.3 Diesel Engines

This report has not explicitly considered diesel engines. Today's diesels are about 15-20 percent more efficient than gasoline engines, which would seem to mandate their inclusion in a study of greatly improved fuel economy. The committee ultimately decided, however, that a diesel case would not add significant value to the results of the study, primarily because the efficiency advantage of the diesel will be much smaller in the future as gasoline engines improve. Current diesels have a much higher level of technology than gasoline engines in order to address diesel drivability, noise, smell, and emission concerns, such as direct fuel injection, sophisticated turbocharging systems using variable geometry or dual turbochargers, and cooled EGR systems. As this same level of technology is added to the gasoline engine, the efficiency advantage of the diesel will be much smaller. Another consideration is that combustion technology by 2050 may blur, if not completely eliminate, the distinction between diesel and gasoline engine combustion. For example, diesel engines are reducing compression ratio in order to increase turbocharger boost and reduce emissions, while gasoline engines are increasing compression ratio due to improvements in combustion chamber design, increasing use of variable valve timing, and better control of EGR. Another example is development of homogenous charge compression ignition engines, which combine features of both gasoline and diesel engines.

2.4.2 Conventional Hybrid Electric Vehicles

HEVs combine an ICE, electric motor(s), and a battery or ultracapacitor. All the energy comes from the fuel for the ICE. HEVs reduce fuel consumption by:

- Turning off the engine during idling, deceleration, and coasting;
- Capturing a percentage of the energy that is normally lost to friction braking (i.e., regenerative braking);
- Engine downsizing (because the electric motor provides a portion of the maximum tractive power required);
- Allowing easier electrification of accessories such as power steering;
- Allowing the engine to operate more efficiently. By using the electric motor to drive the wheels at low load, or by operating the engine at a higher power (and higher efficiency) during low loads and capturing excess energy in the battery; and
- By allowing the use of efficient engine cycles, e.g. Atkinson cycle, that are impractical for conventional drivetrains.

The simplest HEV configuration has a "stop-start" system which shuts off the engine when idling and restarts it rapidly when the accelerator is depressed. These "micro-hybrids" need a higher capacity battery and starter motor than ICEVs. Stop-start systems are rapidly growing and are likely to be universal by 2030 because they are a relatively inexpensive way to achieve substantial fuel economy improvements. The benefits of stop-start systems are included in the committee's calculations for future ICEV efficiency. The hybrid vehicle projections assess the incremental efficiency above that of the stop-start system.

More complex systems that allow electric drive and substantial amounts of regenerative braking include parallel hybrid systems with a clutch between the engine and the motor, commonly referred to as P2 parallel hybrids (e.g., Hyundai Sonata hybrid). They have an electric motor inserted between the transmission and wheels, with clutches allowing the motor to drive the wheels by itself or in combination with the engine, or allowing the engine to drive the wheels without motor input. Powersplit hybrids (e.g., Prius) are another approach, with two electric machines connected via a planetary gearset to the engine and the powertrain. The committee determined that there is more opportunity for cost reduction on P2 hybrid systems in the future and used P2 systems for the future hybrid efficiency and cost assessments (see Appendix F).

About 60 percent of the fuel energy in an ICE is rejected as heat, roughly evenly divided between the engine cooling system (through the radiator) and the exhaust. Some of this heat can be recovered and used to reduce fuel consumption, especially from the exhaust, which is at a high temperature. Turbines, such as used for turbo-chargers, can generate electric power or transfer power to the crankshaft. Alternatively, thermoelectric couples can generate electric power directly, reducing fuel consumption by about 2 to 5 percent. HEVs would likely benefit more than ICEVs from waste heat recovery, as generated electric power could be used in their hybrid propulsion systems or to recharge the battery. This analysis assumes waste heat recovery systems will be applied starting in 2035, and only to HEVs. More efficient forms of waste heat recovery, such as Rankine cycle devices, were not included in the analyses.

There is some uncertainty about the fuel consumption benefit of advanced hybrid systems in the future. While hybrid systems will improve (more efficient components, improved designs and control strategies), advanced engines will reduce some of the same losses that hybrids are designed to attack (e.g., advanced engines will have reduced idle and braking fuel consumption, yielding less benefit from stopping the engine during braking and idling). In addition, even as hybrid drivetrains improve, conventional ICE fuel consumption will shrink, and the actual volume of fuel saved will go down. As done for ICEVs, the committee used the Ricardo simulations of 2025 hybrid vehicles to directly estimate losses and efficiency for the optimistic case in 2025 and for the midrange case in 2030. Unfortunately, Ricardo did not conduct simulations of baseline hybrid systems, so the annual rate of improvement from 2010 to 2025/2030 was assessed using Ricardo's ICE baseline simulations and differences in the 2025 simulations for ICE and hybrid vehicles to establish baseline hybrid energy losses. The committee's estimates are shown in Table 2.3.

TABLE 2.3 Estimated Future Average Fuel Economy and Fuel Consumption

	Cars				Trucks			
	Midrange		Optimistic		Midrange		Optimistic	
	ICE	HEV	ICE	HEV	ICE	HEV	ICE	HEV
Average Fuel Economy (miles per gallon)								
2010	31	43	31	43	24	32	24	32
2030	65	78	74	92	46	54	52	64
2050	87	112	110	145	61	77	77	100
Average Fuel Consumption (gallons per 100 miles)								
2010	3.20	2.34	3.20	2.34	4.24	3.10	4.24	3.10
2030	1.55	1.28	1.36	1.09	2.19	1.84	1.91	1.56
2050	1.15	0.89	0.91	0.69	1.64	1.30	1.30	1.00

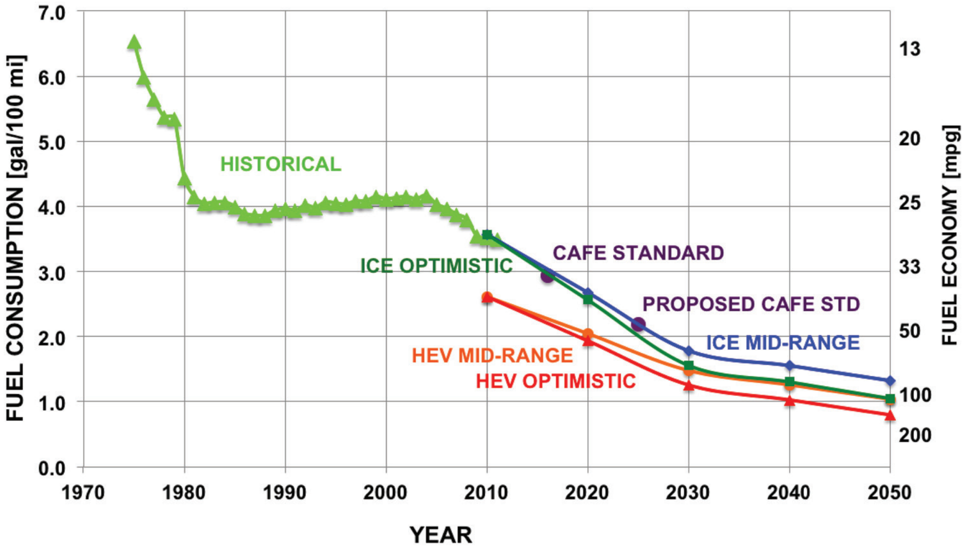

FIGURE 2.1 Historical and projected light-duty vehicle fuel economy.
NOTE: All data is new fleet only using unadjusted test values, not in-use fuel consumption.

While the gains projected by the committee are clearly ambitious, the rate of improvement for conventional vehicles (including use of stop-start systems and advanced alternators) is about 3 percent/year from 2010-2050. Light-duty trucks are expected to improve almost as much. Figure 2.1 compares these rates of improvement to past experience and the 2016 and 2025 CAFE standards. All of the vehicle modeling was assessed as percentage improvements over baseline vehicles. These results were adjusted by the ratio of the baseline used for the modeling in Chapter 5 to the average efficiency of the baseline vehicles used in Chapter 2.

The committee estimated HEV costs by adding the cost of the battery pack, electric motor, and other hybrid system components to the cost previously estimated for conventional vehicles. Credits were also applied for engine downsizing and deletion of the torque converter and original equipment alternator, with the exception that engine size was not reduced on body-on-frame light trucks in order to maintain towing capacity. Weight and other load reductions were incorporated into calculations of the size of the engine, motor, and battery pack for each of the six vehicles. Credits associated with engine downsizing and eliminating the torque converter were subtracted. Except for the battery pack, hybrid system costs were based on detailed and transparent tear-down cost assessments conducted by FEV, Inc., on current production HEV vehicles, with learning factors and suitable design improvements applied to future HEV vehicles (FEV, 2012). Batteries are discussed in Section 2.5, below.

Currently, an HEV costs about $4,000 to $5,000 more than an equivalent ICEV, mostly for the battery, electric motor, and electronic controls. The committee's total direct manufacturing cost increments for hybrids, compared with 2010 reference vehicles, are shown in Table 2.4. Details on projected costs for hybrid systems are in Appendix F. Retail

TABLE 2.4 Efficiency Cost Increment Over Baseline 2010 Vehicle

	Cars				Trucks			
	Midrange		Optimistic		Midrange		Optimistic	
	ICE	HEV	ICE	HEV	ICE	HEV	ICE	HEV
2010	$0	$4,020	$0	$4,020	$0	$4,935	$0	$4,935
2015	$435	$3,510	$376	$3,006	$460	$4,228	$400	$3,601
2020	$986	$2,989	$867	$2,485	$1,059	$3,516	$939	$2,890
2025	$1,652	$3,017	$1,473	$2,590	$1,798	$3,446	$1,618	$2,942
2030	$2,433	$3,280	$2,195	$2,765	$2,676	$3,711	$2,436	$3,160
2035	$2,675	$3,357	$2,432	$2,973	$2,978	$3,834	$2,734	$3,408
2040	$2,960	$3,638	$2,713	$3,267	$3,332	$4,171	$3,085	$3,770
2045	$3,288	$3,949	$3,036	$3,577	$3,738	$4,540	$3,487	$4,142
2050	$3,659	$4,347	$3,403	$3,960	$4,196	$5,022	$3,941	$4,611

price markups are discussed in Chapter 5. Additional information on how the committee arrived at its estimates of fuel economy improvements and direct manufacturing costs are in Appendix F.

2.5 PLUG-IN ELECTRIC VEHICLES

Three distinctly different configurations that utilize battery power for propulsion are in production: HEVs, discussed in the previous section; PHEVs; and BEVs. Each has a rechargeable battery designed for a specific service. The Chevrolet Volt is the first mass-produced PHEV,[9] and Nissan's Leaf the first mass produced BEV[10] introduced into the U.S. market. Other manufacturers are introducing electric vehicles of both types over the next several years. Improvements in battery technology will be critical to the success of electric vehicles.

Plug-in hybrids are conceptually similar to HEVs. The same set of improvements in fuel economy that will benefit HEVs will also benefit PHEVs. PHEV batteries have about 4-20 kilowatt-hours (kWh) of stored energy that can be charged from the grid. PHEVs can travel 10 to 40 miles on electricity before the engine is needed. Thus a driver who does not exceed the electric range and charges the vehicle before using it again will use little or no gasoline. However, when driven beyond the charge depletion mode of the first 10 to 40 miles, the vehicles operate as conventional hybrid vehicles (in a charge sustaining mode), eliminating the range anxiety associated with BEVs. PHEV efficiency was assumed to be the same as BEV efficiency when operating on the battery pack and the same as HEV when the engine is running.

A BEV has no engine, a significant cost savings relative to PHEVs, but currently the battery pack for even a small, short-range vehicle is likely to be at least 20 kWh, and a large SUV might require 100 kWh for a range of 200 miles. The Nissan Leaf has a battery of 24 kWh. Battery cost will thus be a key determinant for the success of PHEVs and BEVs. Based on the energy modeling described earlier in this chapter, a car that today gets 30 mpg would, if built as a BEV, require about 26 kWh/100 miles. For a range of 300 miles, the battery would need at least 78 kWh of available energy.[11] With current technology and costs, this would be prohibitively expensive, heavy, and bulky for most applications and would take prohibitively long to charge. At $450/kWh, the current battery pack cost estimate (see Section 2.5.3 below), a 78 kWh battery costs $35,000. Prospects for reducing the cost are discussed below.

Other considerations for plug-in vehicles include the range that can be achieved in an affordable vehicle and the time required for recharging. As vehicle weight, aerodynamic resistance, and rolling resistance are improved, range can be improved for the same battery size, or a smaller, less expensive battery may be used for the same range. Many PHEVs and BEVs can be plugged in at home overnight on regular 110 or 220 volt lines. Gradual charging is generally best for the batteries, and night-time charging is best for the power supplier, as power demand is lower than during the day and excess generating capacity is available (see Chapter 3). Fast charging is more challenging for batteries, requires more expensive infrastructure, and is likely to use peak-load electricity with higher cost, lower efficiency, and higher GHG emissions.

2.5.1 Batteries for Plug-In Electric Vehicles

There is general agreement that the Li-ion battery will be the battery of choice for electric vehicles for the foreseeable future. It was developed for the portable electronics industry 20 years ago because of its light weight, superior energy storage capability, and long cycle life, attributes, which also are important for electric vehicles. Cell performance has increased steadily by improvements in the internal electrode structure and cell design and manufacturing processes, as well as the introduction of higher performance anode and cathode materials.

There are several Li-ion chemistries that are being investigated for use in vehicles, but none offers an ideal combination of energy density, power capability, durability, safety, and cost. HEVs are also shifting to Li-ion from the original nickel-metal-hydride chemistry. HEV batteries, which are optimized for high power, may differ from those for PHEVs and BEVs, which will be optimized for high energy and low cost.

Development of the cylindrical 18650 Li-ion cell for the portable electronics industry is representative of how automotive batteries may develop. In 1991, the cost of the 18650 was $3.17/Wh. Twenty years later, the same cell costs $0.20/Wh, while the charge capacity of the cell went from 1 Amp-hour (Ah) to over 3 Ah in the same volume (see Figure 2.2). These improvements resulted from the introduction of new, high-performance materials, improvements to the cell and electrode structure design, and high volume production processes with reduced wastage. As a rule of thumb for highly automated cell production, cell materials account for about 60 to 80 percent of the cell cost in volume production.[12]

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[9] The Volt's all-electric range is certified by EPA as 38 miles. General Motors refers to the Volt as an extended range electric vehicle because all power to the wheels is delivered by the electric motor, unlike, say, Toyota's Prius PHEV. However, both are hybrids in that they have two fuel sources.

[10] The EPA certified range is 73 miles, but estimates vary widely; also, range is extremely sensitive to weather, driving conditions, and driver behavior.

[11] Available energy is typically less than nameplate battery pack capacity because batteries may not completely discharge to avoid damage to battery life and loss of power. In addition, available energy could effectively be reduced by energy required to offset the loss of vehicle efficiency caused by the additional weight of a larger battery for longer range.

[12] As used here, "materials" means processed materials ready for cell manufacture. It does not mean raw materials, which may be much cheaper.

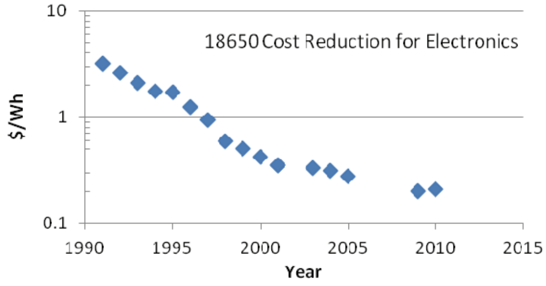

FIGURE 2.2 Cost of the 18650 portable electronics Li-ion cell (current dollars).
SOURCE: H. Takeshita, Tutorials, Florida International Battery Seminars, 1974-2010.

Cells for vehicles are likely to be prismatic (flat plate) or pouch-type rather than cylindrical, because these are easier to cool and arrange in stacks. The production process for flat plate vehicle cells differs from that for cylindrical cells, but it is anticipated that the cost will follow a similar learning pattern as the 18650 cell. Both the Volt and Leaf use a manganese spinel cathode and a graphite anode in a flat-plate configuration with a $LiPF_6$ electrolyte for long cycle life and relatively low cost.

Global R&D activity in Li-ion battery technology is funded at a level of several billion dollars annually. It explores all aspects of the technology and aims to improve energy-storage capacity per unit weight and volume, durability, safety characteristics, operating temperature range, manufacturing processes, and of course cost. Technologies that will offer improved performance without negatively affecting safety, durability, and cost, or, alternatively, improved cost without negatively affecting durability and safety are the only ones likely to find high-volume commercial application. In the next five years or so, optimization of the use of existing materials, engineering optimization of cell and component design, manufacturing process improvement, and economy of scale will support moderate improvements in performance and steady reduction in cost. In the longer term (8 to 15 years), introduction of materials with higher energy density could provide enhanced performance. Further out, probably beyond 2030, new chemistry may be developed but at this point in time no chemistry other than Li-ion is promising enough to be included in this analysis.

2.5.2 Automotive Battery Packs

A battery pack for vehicles consists of an assembly of cells, electrical components, structural components, a cooling system, module management electronics, and battery management system (BMS). A typical pack consists of 30 to several hundred cells configured in a series/parallel arrangement. The series arrangement includes 30 to 100 "virtual" cells in strings that provide a battery voltage of 100 to 400 volts. The virtual cells include a single cell or several cells in parallel to provide the desired Ah capacity. In other combinations, several strings could be put in parallel to provide the total energy capacity required. Cells typically represent 50 to 60 percent of the cost of a battery in HEV applications, 60 to 70 percent of the cost of the pack in PHEV applications and 70 to 80 percent of the cost of pack in BEV applications. The BMS, structural components, electrical components, cooling systems, and assembly account for the balance. While the non-cell portion of the pack grows in complexity and cost from HEVs to PHEVs to BEVs, the number and cost of the cells increases faster.

The BMS is designed to maximize battery life, to minimize the risk of safety incidents, and to communicate to the vehicle controller the state of charge and state of health of the battery. The BMS monitors individual cell voltages, battery current, and battery temperature (measured in several places in the pack). When abnormal cell voltages, temperatures or current are measured, the BMS "takes action" to minimize damage to the battery or risk of safety events.

2.5.3 Battery Cost Estimates

Estimates of future vehicle battery costs vary widely and depend greatly on assumed production levels as well as technology development. Even current costs are uncertain because of proprietary information, and battery companies may sell batteries below costs in order to gain market share in the early stages of growth. The committee assumed that future costs of Li-ion cells for vehicles are likely to follow a similar (but dropping somewhat more gradually) trajectory as that for the 18650 cell shown in Figure 2.2. Those costs fell in a regular manner for 10 years and then began to level off as production processes matured and improved in reliability. Costs of the battery pack (in addition to the cells) also should decline at about the same rate as cells as manufacturers and suppliers improve designs and production techniques.

The starting point for the committee's projected costs for BEV battery packs in Figure 2.3 is $450/kWh for high rates of production.[13] Midrange BEV pack costs for 2030 are estimated at $250/kWh and $160/kWh in 2050. Optimistically, pack costs might reach $200/kWh in 2030 and $150/kWh in 2050.

The battery packs used in PHEVs, FCVs, and HEVs are smaller and must still provide high levels of power. This requires the use of batteries with higher power densities, which increases the cost per kWh of energy storage. PHEV pack costs are likely to be $60-70/kWh higher than BEV pack costs. HEV costs are highest because they are much smaller and require different characteristics. Batteries for

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The processing of these materials is subject to considerable cost reduction, as is the cell manufacture.

[13] Actual costs for the Leaf and Volt battery packs in 2012 are estimated at about $500/kWh, which reflect lower production volumes. However, note that the Leaf battery does not have a liquid cooling system, and the packs may deteriorate faster. Hence that cost may not be typical.

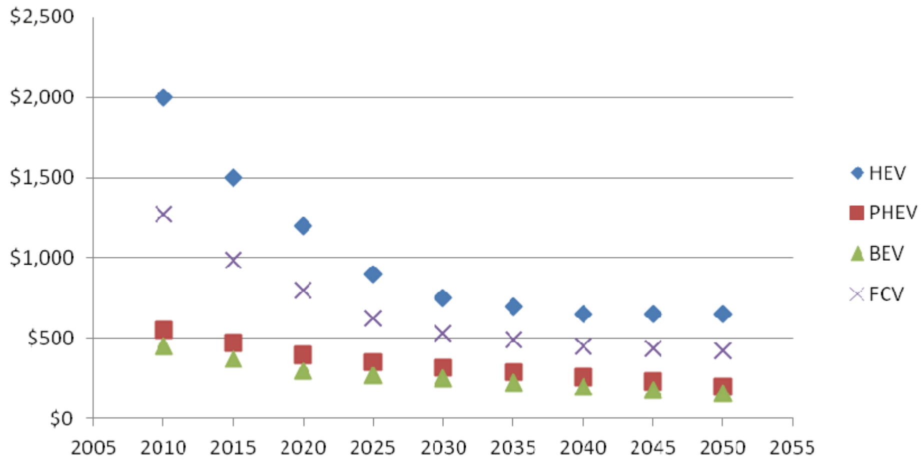

FIGURE 2.3 Estimated battery pack costs to 2050 ($/kWh).

fuel cell vehicles are between HEVs and PHEVs, as discussed later. Details on the committee's assessment of batteries are in Appendix F.

Using costs in Figure 2.3, the committee's estimate for a 30 mile range, as shown in Appendix F, is $4,000 (optimistic) to $4,600 (midrange). In comparison, DOE's 2015 goal for a battery pack for a PHEV with a 10-mile all-electric range in 2015 is $1,700 and $3,400 for a 40-mile range (Howell and Elder, 2012). PHEV battery costs depend on assumptions such as available energy (state of charge range) as well as how deterioration is handled and the vehicle that is to be propelled, but in general, the committee's assessment is less optimistic than DOE's targets.

A battery recycling effort will be needed when large numbers of battery packs reach the end of their useful lifetimes, and that will help to control costs. Recycling already works well for lead acid batteries, almost all of which are returned and the components reused in construction of new batteries.

2.5.4 Battery Technology for Future Applications

Li-ion battery technology for automotive applications may be limited to about 250 to 300 Wh/kg and $175 to $200/kWh (all at the pack level), although this report estimates that costs could get down to $150/kg by 2050. Research work around the world is examining other potential technologies that can yield higher energy density and/or lower cost per unit of energy. As noted before, none of the more futuristic systems has achieved enough maturity to be considered in this evaluation. Lithium sulfur chemistry utilizes a lithium metal anode and a cathode based on sulfur compounds. That system could theoretically double the specific energy of Li-ion batteries and offer competitive cost, but to date the cycling of both electrodes is quite problematic. Even more attention is given to the Li-Air chemistry. This chemistry utilizes lithium-metal anodes and an air electrode so that the cathodic active material (oxygen) is taken from the air and at the charged state does not add to the weight of the battery (the battery gains weight as it discharges). This chemistry can theoretically provide a battery system with a specific energy of several kWh/kg. However, there are multiple independent technical challenges including the cyclability of the lithium electrode, cyclability of the air electrode, charge and discharge rate capability of the air electrode, finding suitable electrolyte, and finding a durable membrane permeable to the electrolyte but impermeable to water and CO_2. Several independent breakthroughs would have to occur to make the technology viable, and overall its chance of success is low.

2.5.5 Electric Motors

Almost all HEVs and PEVs use rare-earth-based interior permanent magnet (IPM) motors. IPM motors are by far the most popular choice for hybrids and EVs because of their high power density, specific power, efficiency, and constant power-to-speed ratio. Performance of these motors is optimized when the strongest possible magnets (NdFeB) are used. Cost and power density (power density equates to torque and acceleration) are emerging as the two most important properties of motors for traction drives in hybrid and EVs, although high efficiency is essential as well.

China currently has a near monopoly on the production of rare-earth materials, and since 2008 it has steadily raised the price of rare-earth magnet materials to as high as $60/kg. An automotive traction motor uses 1 to 1.5 kg of rare-earth magnet materials, which influences the cost of motors for electric vehicles.

The potential for a future shortage of rare-earth materials has led DOE to search for technologies that either eliminate or reduce the amount of rare-earth magnets in motors. The

TABLE 2.5 Motor Cost Estimates

	HEV/PHEV Costs		BEV/FCEV Costs	
	Fixed	$/kW	Fixed	$/kW
Midrange				
2010	$668	$11.6	$668	$11.6
2030	$393	$6.3	$425	$7.3
2050	$322	$5.2	$347	$6.0
Optimistic				
2010	$668	$11.6	$668	$11.6
2030	$349	$5.5	$381	$6.5
2050	$286	$4.5	$311	$5.3

DOE strategy continues ongoing cost-reduction efforts for rare-earth-based motors while also searching for new permanent magnet materials that do not use rare earths and motor designs that do not use permanent magnets.

Recently Toyota announced that it has developed a new material with equivalent or superior capability as rare-earth materials for the electric motors in its line of electric vehicles (Reuters, 2012). Toyota has also developed an induction motor that it claims is lighter and more efficient than the magnet-type motor now used in the Prius and does not use rare-earth materials.

In addition, U.S. production of rare-earths is resuming. Therefore, rare-earth materials are not likely to cause major increases in motor costs in the future. Overall, motor costs are likely to decline from about $2,000 now to less than $1,000 in 2050 for a typical electric car. This decline will result from better design and manufacturing and from the smaller size that will be needed to power more efficient future vehicles.

Table 2.5 presents the committee's motor cost estimates. These are based upon detailed tear-down cost estimates by FEV and include the cost of the motor, case, launch clutch, oil pump and filter, sensors, connectors, switches, cooling system, motor clutch, power distribution, and electronic control module. Some costs are independent of the size of the motor within the range considered here (fixed), and others are directly dependent (variable). Future cost projections included learning and incorporation of the electric motor into the transmission for HEV and PHEV applications. Further details on electric motors are in Appendix F.

2.5.6 Barriers to the Widespread Adoption of Electric Vehicles

2.5.6.1 Battery Cost

Cost is a key issue for the success of the electric vehicle. Lower cost electrode materials will be an important step. Cathode, separator and electrolyte are the main contributors to the cell cost. Most of the new cathode materials are composed of high cost nickel and cobalt materials. However, lower cost, lower performance materials such as lithium iron phosphate and manganese spinel for cathodes and graphite for anodes can be made for about $10/kg or less in large volume. Battery pack costs per kWh are expected to decline by as much as two-thirds by 2050, as noted above, and pack size will also decline as vehicles become more efficient.

2.5.6.2 BEV Range and Recharge Time

Even with expected cost reductions, batteries will still be expensive and bulky, limiting the size that can be installed in most vehicles. BEVs must have reasonable range at reasonable cost if they are to widely replace ICEVs. The average conventional vehicle has a range of at least 300 miles on a tank of gasoline, but more range in a BEV requires a bigger battery, and that raises costs significantly as discussed above. Very few affordable BEVs will greatly exceed 100 miles for the next several years and possibly much longer. An even larger problem is recharge time. Unless batteries can be developed that can be recharged in 10 minutes or less, BEVs will be limited largely to local travel in an urban or suburban environment.

Battery swapping is being tested as a solution to the range and recharge time problems. A vehicle with a nearly discharged battery pack would drive into a station where a large machine would extract the pack and replace it with a fresh one. While battery swapping would, if widely available, solve the recharging and range problems, it also faces significant problems: (1) vehicles and battery packs would have to be standardized; (2) the swapping station would have to keep a large and very expensive inventory of different types and sizes of battery packs; (3) swapping stations are likely to start charging the incoming batteries right away in order to have them available for the next vehicle, possibly aggravating grid peaking problems; (4) batteries deteriorate over time, and customers may object to getting older batteries, not knowing how far they will be able to drive on them; and (5) most battery swapping will occur only when drivers make long trips, thus seasonal peaks in long-distance travel, e.g., during holidays, are likely to aggravate inventory problems. Although Israel has begun development of a battery swapping network and other countries appear to be considering it, the committee considers it unlikely that battery swapping will become an important recharging mechanism in this country.

2.5.6.3 Durability and Longevity

Battery life expectancy is a function of battery design and manufacturing precision as well as battery operating and charging behavior. Rapid charging and discharging can shorten the lifetime of the cell. This is particularly important because the goal of 10 to 15 years service for automotive applications is far longer than for use in electronic devices. Current automotive batteries are not expected to last for 15 years, the average lifetime of a car. Replacing the battery would be a very expensive repair, even as costs decline. Thus improved longevity is an important goal.

2.5.6.4 Safety

Battery safety is a critical issue. There are three major components that characterize the safety of a battery pack: the failure rate of an individual cell, the probability of propagation of a single cell fault to the pack, and the failure rate of the electronics. Li-ion batteries are high-energy-density systems that utilize a flammable electrolyte and highly reactive cathode and anode materials separated by a thin micro-porous separator. The potential thermal energy in the cell is much larger than the electro-chemical energy because the electrolyte is flammable in air and most anodes are metastable compounds that require kinetic protection at the surface. Li-ion cells contain sufficient energy to heat the cell to over 500°C if this energy is released rapidly inside the cell. That could cause neighboring cells to also fail, leading to a catastrophic event. Ensuring safe operation of vehicles that utilize large Li-ion batteries is a significant engineering task that includes the following:

a. Protection from overcharge;
b. Protecting the battery cells from deforming during crash;
c. Reducing the likelihood of an internal short that could develop due to poor cell design or to a manufacturing defect (BMS should remove the cell from the circuit);
d. Designing a cell in such a way that even if an internal short does occur, it does not lead to thermal runaway of the cell;
e. Designing the BMS in such a way that even if a single cell experiences thermal runaway, the process does not propagate to neighboring cells and to the pack; and
f. Avoiding external shorts of the whole battery or sections of it during installation, servicing, or normal usage.

Cell, battery, and vehicle engineers have developed multiple tests to assess the ability of the cell, battery, and vehicle to operate without endangering human life. In most tests, battery failure is allowed but fire or explosions are unacceptable.

The failure rate for Li-ion 18650 cells equates to a reliability rate of about 1 out of 10,000. This level of reliability is not satisfactory for electric vehicle batteries, where 1 out of a million is the minimum required (Takeshita, 2011). Therefore, it is essential to essentially eliminate cell construction defects in the individual cells, as well as defects in the battery pack electronics, in order to virtually eliminate the chances of a catastrophic event. Since increasing the energy density of the cell is associated with an increase of the thermal energy available per unit weight and volume, insuring safety while increasing energy density is particularly challenging.

2.6 HYDROGEN FUEL CELL ELECTRIC VEHICLES

The hydrogen FCEV is an all-electric vehicle similar to a BEV except that the electric power comes from a fuel cell system with on-board hydrogen storage. FCEVs are commonly configured as hybrids in that they use a battery for capturing regenerative braking energy and for supplementing the fuel cell output as needed. Power electronics manage the flow of energy between the fuel cell, battery and electric motor.

The fuel cell system consists of a fuel cell stack and supporting hardware known as the balance of plant (BOP). The fuel cell stack operates like a battery pack with the anodes fueled by hydrogen gas and the cathodes fueled by air. The BOP consists of equipment and electrical controls that manage the supply of hydrogen and air to the fuel cell stack and provide its thermal management. The vehicle is fueled with hydrogen at a fueling station much like gasoline fueling, and hydrogen is stored on the vehicle as a compressed gas or cryogenic liquid in a storage tank.

The key advantages of FCEVs include the following:

- High energy efficiency;
- No tailpipe emissions—neither GHG nor criteria pollutants—other than water;
- Quiet operation;
- Hydrogen fuel can be produced from multiple sources, thereby enabling diversity in energy sources (including low carbon and renewable energy sources) away from near-total reliance on petroleum;
- Full vehicle functionality for safe on-road driving, including 300-mile driving range;
- Rapid refueling; and
- Source of portable electrical power generation for off-vehicle use.

The key challenges of FCEVs are the following:

- Demonstration of on-road durability for 15-year service life;
- Maturation of the technology for cost reduction, greater durability, and higher efficiency; and
- Availability of fuel while few FCEVs are on the road and the eventual production and distribution of hydrogen at competitive costs (discussed in Chapter 3).

Several companies (e.g., Hyundai, Daimler, Honda, and Toyota) have announced plans to introduce FCEVs commercially by 2015, but mainly in Europe, Asia, California, and Hawaii where governments are coordinating efforts to build hydrogen infrastructures.

2.6.1 Current Technology for Hydrogen Fuel Cell Electric Vehicles

2.6.1.1 Fuel Cell Powertrain

The power electronics and electric motor/transmission are similar in efficiency and cost as for PHEVs and BEVs. Future improvements in the performance and cost of those systems will apply to FCEVs as well.

The battery in FCEVs has comparable power but greater energy content than that in current HEVs because it must power driving for 2 to 5 miles while the fuel cell warms up in cold weather. The fuel cell must be sized for nominal driving requirements and efficient operation. The battery will recharge from the fuel cell directly and through regenerative braking.

Over the past decade, FCEVs used in demonstration fleets have shown significant technology advances toward commercial readiness in the areas of performance and cost. For example, the cost of automotive fuel cell systems has been reduced from $275/kW in 2002 to $51/kW in 2010 (based on projections of high-volume manufacturing costs), and vehicle range has increased to at least 300 miles (James et al., 2010). Vehicles have demonstrated the capability to meet all urban and freeway driving demands. A remaining development challenge is proving the capability for high load driving at high ambient temperatures.

2.6.1.2 Fuel Cell Systems

Fuel cell stacks currently used in automotive applications are based on the polymer-electrolyte membrane/proton-exchange membrane (PEM). PEMs operate at moderate temperatures that can be achieved quickly so they are suitable for the infrequent and transient usage of on-road automotive service. Catalysts using precious metals (primarily platinum) are needed to promote the hydrogen/oxygen reaction that generates electricity in the fuel cell stack. Improvements in stack durability, specific power and cost have resulted from methods to improve the stability of the active catalytic surface area, and from new membrane materials and structures. For example, stack lifetimes of 2,500 operating hours (equivalent to approximately 75,000 mile range) have been demonstrated in on-road vehicles, and laboratory tests with newer membrane technologies have demonstrated (using accelerated test protocols) over 7,000 hours.

The BOP consists primarily of mature technologies for flow management of fluids and heat. Significant improvements in efficiency and cost result from continuing simplifications in BOP design, as illustrated in Figure 2.4.

Further reductions in the cost of fuel cell systems are expected to result from down-sizing associated with improved stack efficiency and improved response to load transients. Significant additional cost reductions will result if vehicle loads (weight, rolling resistance, and aerodynamics) are reduced because that will allow the use of smaller hydrogen tanks and fuel cells with lower total power.

2.6.1.3 Fuel Cell System Efficiency

Fuel cell system efficiency measured for representative FCEVs driven on chassis dynamometers at several steady-state points of operation has shown a range of first-generation net system efficiencies from 51 to 58 percent. Second-generation vehicle systems have shown 53 to 59 percent efficiency at one-quarter rated power. System efficiency has improved slightly while the major design changes have focused instead on improving durability, freeze performance, and cost (Wipke, 2010a,b). With current fuel cell system efficiencies, fuel storage capacity and vehicle attributes (weight, aerodynamics, rolling resistance), FCEVs are currently capable of 200 to 300 miles of real-world driving range, and fuel efficiency over twice that of the comparable conventional ICEV.[14]

2.6.1.4 Fuel Cell System Cost

Projected costs for high volume production of fuel cells have dropped steeply with improved technology, dropping to $51/kW in 2010 for the fuel cell system, as shown in Figure 2.5. The fuel cell stack generally accounts for 50 to 60 percent of the system cost. Costs are very sensitive to production volume as shown in Figure 2.6.

2.6.1.5 Onboard Hydrogen Storage

Hydrogen storage costs are a significant element in the overall costs of a FCEV. Compressed gas at 5,000 psi (35 MPa) or 10,000 psi (70 MPa) has emerged as the primary technology path for the introduction of FCEVs because it is a proven technology that can meet the needs of the fuel cell (Jorgensen, 2011). Other possible future means of hydrogen storage (cryogenic or solid state) that have not been deployed in FCEV fleets were not considered by the committee.

The compressed gas storage capacity, and hence the vehicle driving range, is limited by the volume and cost of tanks that can be packaged in vehicles. Driving ranges over 300 miles are expected to be achieved, and a 300 mile real-world range, plus a 10 percent reserve, was used by the committee to calculate the size and cost of the storage tank.

Carbon-fiber reinforced composite (CFRC) tanks have been employed to achieve sufficient strength at manageable weight. Detailed cost analyses in Appendix F show total costs for representative 5.6 kg usable hydrogen systems are $2,900 for 35 MPa and $3,500 for 70 MPa (Hua et al., 2011). Car-

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[14] 2011 Honda Clarity: ICEV fuel economy = 27 mpg, FCEV fuel economy > 60 mpg, with both mpg values based on (adjusted) fuel economy label values; ICEV fuel economy based on EPA, 2012; FCEV fuel economy from DOE, 2012a.

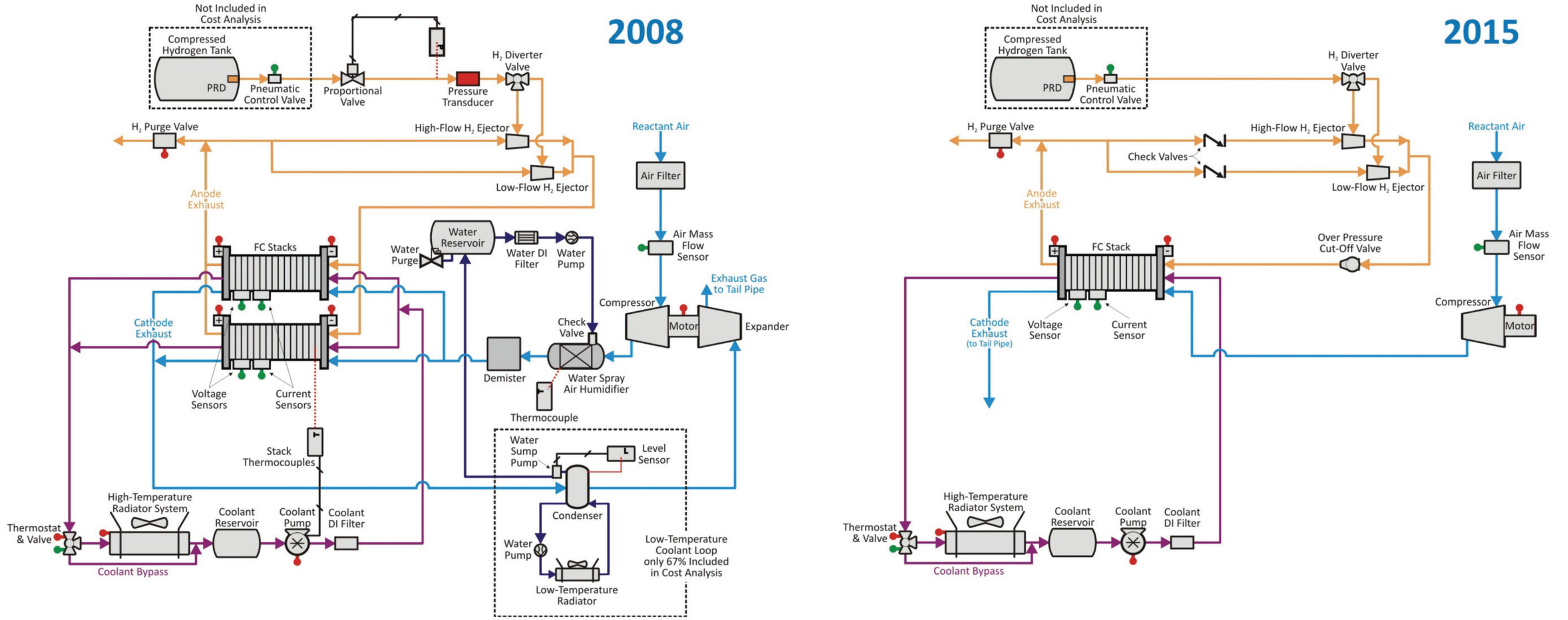

FIGURE 2.4 Continuing system simplification contributes to cost reduction.
SOURCE: James et al. (2010).

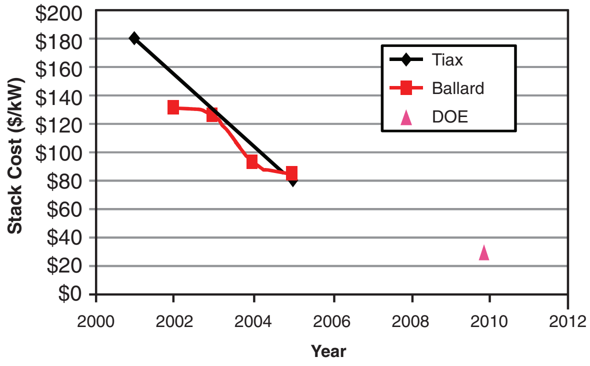

FIGURE 2.5 Historical progression of high-volume fuel-cell stack cost projections.
SOURCES: Kromer and Heywood (2007), NRC (2005, 2008), and Carlson et al. (2005).

bon fiber, priced at roughly $30/kg of the hydrogen stored, accounts for most of the cost of the CFRC wrapped layers that provide the structural strength of the storage system. The remaining costs are primarily attributed to flow-regulating hardware.

2.6.1.6 Vehicle Safety

The two primary features that distinguish FCEVs from ICEVs with respect to safety are high-voltage electric power and hydrogen fuel. The safety of high voltage electric power is managed on FCEVs similarly to HEVs, where safety requirements have resulted in on-road safety comparable to that of ICEVs. Experience from decades of safe and extensive use of hydrogen in the agriculture and oil refining industries has been applied to vehicle safety, and verified in vehicle maintenance and on-road demonstration programs. Fire risk is mitigated because hydrogen dissipates much faster than do gasoline fumes and by regulatory provisions for fuel system monitoring. The safety of high-pressure onboard gaseous fuel storage has been demonstrated worldwide in decades of use in natural gas vehicles. Comparable safety criteria and engineering standards, as applied to ICEVs, HEVs, and CNGVs, have been applied to FCEVs with adaptation of safety provisions for differences between properties of natural gas and hydrogen. The United Nations has drafted a Global Technical Regulation for hydrogen-fueled vehicles to provide the basis for globally harmonized vehicle safety regulations for adoption by member nations (UNECE, 2012). Codes and standards will also be required for hydrogen fueling stations, as discussed in Chapter 3, but DOE has greatly reduced its work in developing them.

2.6.2 FCEV Cost and Efficiency Projections

Detailed analyses of current fuel cell costs and near-term improvements yield an estimated fuel cell system cost estimate of $39/kW for a high volume FCEV commercial introduction in 2015 (James 2010). This estimate reflects recent advances in technology and material costs, especially sharp reductions in the loading of precious metal in fuel cell electrodes. The platinum (Pt) loading in an earlier-generation 100 kW stack with ~80 g Pt at $32/g (2005 Pt price) would cost ~$2,500. For the 2010 loading of only 10 g Pt in a higher-technology alloyed-Pt 100 kW stack, the cost would be only ~$600 even at the higher 2011 Pt price of $58/g.

The committee estimates a midrange fuel cell system cost of $40/kW in 2020, and an optimistic cost of $36/kW, assuming additional cost benefit from potential near term technology developments. All cost estimates assume commercial introduction of FCEVs at annual production volumes over

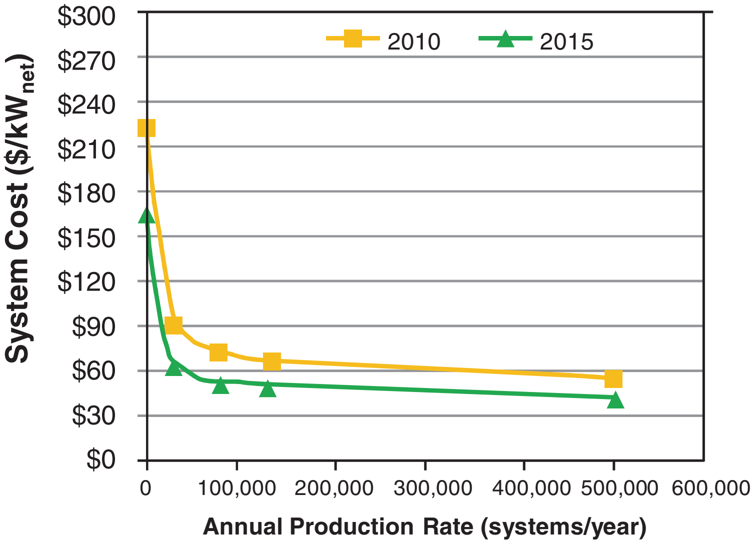

FIGURE 2.6 Progression of fuel cell system costs with production volume.
SOURCE: James et al. (2010).

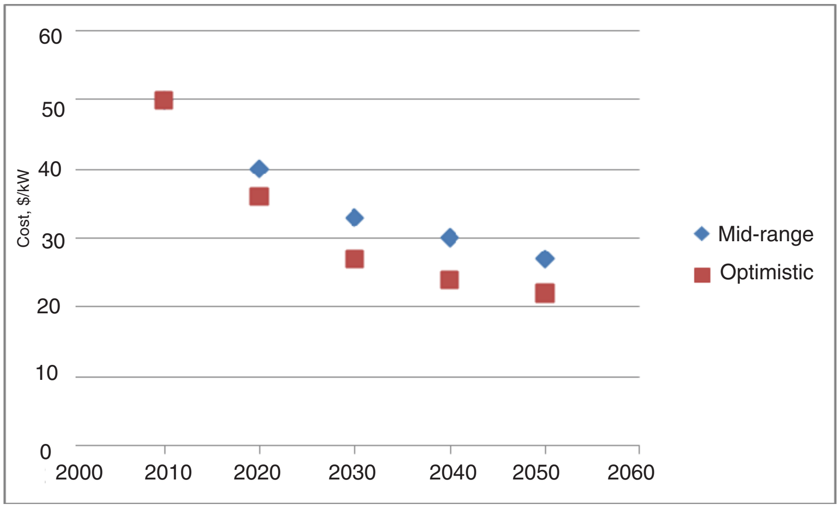

FIGURE 2.7 Fuel cell system estimated costs.

200,000 units, with the primary economy of scale occurring at 50,000 units (James, 2010).

Costs are likely to drop more rapidly in the earlier years of deployment because automotive fuel cell systems are in an early stage of development. Historically, reductions in weight, volume and cost and improvements in efficiency between successive early generations of a new technology are much more substantial than between more mature generations. Reductions of 2.3 percent per year in high volume cost in early generations of a technology, and 1 percent per year in later generations have commonly been observed. Therefore, for purposes of this report, technology-driven cost reductions from 2020 to 2030 of 2 percent per year were used for the midrange case and 3 percent per year for the optimistic case. This report assumes that improved technology will reduce costs by 2030 to $33/kW for the midrange and $27/kW for the optimistic scenarios.

Because of the major focus of fuel cell research and development on cost reduction prior to 2030, the committee expects that subsequent cost reduction rates will be slower, at 1 percent per year. By 2050, the midrange cost estimate is $27/kW and the optimistic is $22/kW. Cost estimates are shown in Figure 2.7. The supporting analysis is in Appendix F.

An evaluation of potential world Pt supply to support FCEVs as 50 percent of the on-road light-duty vehicle sales by 2050 assumed the conservative achievement of 15 g Pt per FCEV by 2050. Key documented findings are that (1) there are sufficient Pt resources in the ground to meet long-term projected Pt demand; (2) the Pt industry has the potential for expansion to meet demand for 50 percent market penetration of FCEVs (15 g Pt/vehicle) by 2050; and (3) the price of Pt may experience a short-term rise in response to increasing FCEV penetration, but is expected to return to its long-term mean once supply adjusts to demand (TIAX LLC, 2003). Scaled to 10 g Pt per FCEV (already achieved by 2010), the same conclusions apply to 80 percent penetration of the light-duty sales by 2050.

TABLE 2.6 Fuel Cell Efficiency Projections

	2010	2020	2030	2050
Midrange	53%	53%	55%	60%
Optimistic	53%	55%	57%	62%

For the foreseeable future, technology developments for fuel cell systems are expected to prioritize reducing the cost of producing a given level of power (kW), rather than efficiency improvements. Therefore, even though significant gains in fuel cell efficiency are theoretically possible, this report assumes only modest improvements from the 2010 level of 53 percent as shown in Table 2.6.[15]

The cost of a CFRC hydrogen storage tank varies with the pressure and volume capacity. In addition, there is a fixed cost, independent of size, from equipment such as valves, pressure regulators and sensors. Reduction in the cost of CFRC tanks can be expected from two sources: new manufacturing/design techniques and the decreasing size of tanks as demand for fuel is reduced with improved vehicle efficiency.

Significant cost reduction from technology advancement is not expected by 2020, but several improvements in processing techniques are expected to reduce the cost of carbon fiber used in CFRC by 25 percent by 2030. The fixed cost fraction, which is associated with flow-control equipment, is expected to have modest potential for cost reduction because the technologies are mature. Therefore, a 1 percent per year cost reduction is applied to the fixed cost fraction, resulting

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[15] The efficiency improvements in Table 2.6 were included in assessing the size and cost of the fuel cell stack.

TABLE 2.7 Illustrative Hydrogen Storage System Cost Projections

	2010	2020	2030	2050
Midrange				
Capacity (kg)	5.5	4.6	3.8	2.8
Cost ($)	3,453	3,031	2,402	1,618
$\$/\text{kg-H}_2$	628	659	632	578
$/kWh	19	20	19	17
Optimistic				
Capacity (kg)	5.5	4.4	3.3	2.4
Cost ($)	3,453	2,938	2,055	1,326
$\$/\text{kg-H}_2$	628	668	623	553
$/kWh	19	20	19	16

in a 10 percent cost reduction in the fixed cost fraction over the 2020-2030 period.

The midrange estimate for 2050 hydrogen storage cost results from continuation of the technology-driven 1 percent per year cost improvement over the 2030-2050 period in recognition of research into improvements in CRFC winding patterns and expectation of further improvements in manufacturing costs from added experience with high-volume production using new techniques (Warren, 2009). Hence, improved technology is estimated to reduce costs by 26 percent between 2020 and 2050. Research on cost reduction of structural CFRC is expected to accelerate with the new market driver of its broadened application to airplane fuselages, and other forms of hydrogen storage could become commercially viable.

Due to the difficulty in confirming promise among early stage research possibilities for manufacturing carbon fibers derived from polyacrylonitrile (PAN), or replacing it as the precursor for carbon fiber, the committee did not assume dramatic cost reductions for CFRC even by 2050. However, it is noted that a reduction in storage cost associated with achievement of a targeted <$10/kg carbon fiber and pressure shift to 50 MPa would be consistent with a cost reduction of 35 to 40 percent, the optimistic technology-driven projection in Table 2.7.

In addition to these technology-related cost projections, additional reductions can be expected when the storage system is down-sized. The volume of hydrogen that needs to be stored for full vehicle range declines as vehicle efficiency increases. This reduction in the variable fraction of the storage cost is directly proportional to the reduced vehicle load.

Promising areas for research and future technology development for improved energy efficiency, performance and cost of fuel cell systems and hydrogen storage are listed in Appendix F.

2.7 COMPRESSED NATURAL GAS VEHICLES

Increasing the use of natural gas in U.S. LDVs would displace petroleum with a domestic fuel, reduce fuel costs, and reduce tailpipe GHG emissions.[16] A key driver of recent interest in natural gas vehicles is the potential from shale-based resources using hydraulic fracturing ("fracking"), and the likelihood that natural gas prices will remain well below gasoline prices for the foreseeable future. The supply of natural gas, and its potential for conversion into liquid fuels, electricity, or hydrogen, are discussed in Chapter 3. This section considers its direct use as a fuel in CNGVs with conventional ICE engines.

Adding a compressed gas storage tank is a larger problem for ICE vehicles than for fuel cell vehicles. This is because vehicle interior space is highly optimized and the large CNG tank compromises the interior space and utility. In contrast, FCEVs eliminate the internal combustion engine and drivetrain, plus the fuel cell stack can be configured in many different ways to optimize interior space. This allows additional room and flexibility for hydrogen storage tanks.

Some vehicles have been converted to burn CNG, but until recently the only dedicated CNG light-duty vehicle sold new in the United States was the Honda Civic Natural Gas vehicle (formerly called the GX). Chrysler has just introduced a CNG pickup, and Ford and General Motors are expected to follow soon. CNGVs have been much more popular in other countries, especially Italy, although sales recently plummeted in Italy after the end of incentives.

2.7.1 Fuel Storage

The key issue is the vehicle storage tank. In order to store enough natural gas for a reasonable driving range, it must be compressed to high pressure. CNGVs can be fast-filled at fueling stations that have natural gas storage facilities and large compressors, or they could be filled overnight, typically at a rate of 1 gallon of gasoline equivalent per hour (gge/hr where gge is the amount of energy equivalent to a gallon of gasoline) at home, tapping into the residential natural gas service and employing smaller compressors.[17]

At 3,600 psi and 70°F, a CNG tank is about 3.8 times larger than a gasoline tank with the same energy content. CNG tanks also are heavier in order to manage the high pressure. The cheapest solid steel (type 1) cylinders weigh 4 to 5 times as much as the same capacity gasoline tank; advanced (Type 3) cylinders with thin metal liners wrapped with composite weigh about half as much as Type 1 tanks, though at higher cost. Tanks with polymer liners weigh even less, but at higher cost. The tank on the 2012 Honda Civic NG vehicle holds about 8.0 gge of CNG at 3,600 psi, giving the vehicle a range of 192 miles (EPA city) to 304 miles

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[16] A CNGV emits about 25 percent less CO_2 than a comparable vehicle operating on gasoline. Upstream emissions of methane, including leakage, are discussed in Chapter 3.

[17] The natural gas must be of sufficiently high quality; Honda does not recommend home refueling at this time because of concern over moisture in the fuel in some parts of the country.

(EPA highway), while taking up half of the vehicle's trunk space. Higher pressure tanks (up to 10,000 psi) can reduce fuel storage space, though at added cost and increased energy required to compress the gas.

In the future, it may be possible to store CNG at 500 psi (within the 200-1500 psi range of the pressure of gas in natural gas transmission pipelines) in adsorbed natural gas (ANG) tanks using various sponge-like materials, such as activated carbon. This technology, which is still under development, could allow vehicles to be refueled from the natural gas network without extra gas compression, reducing cost and energy use and allowing the fuel tanks to be lighter. Also, at lower pressure, the shape of the tank can be adjusted as needed to fit the space available, thus minimizing the impact on cargo space. The committee did not include ANG tanks in its modeling.

2.7.2 Safety

When used as an automobile fuel, CNG is stored onboard vehicles in tanks that meet stringent safety requirements. Natural gas fuel systems are "sealed," which prevents spills or evaporative losses. Even if a leak were to occur in a fuel system, the natural gas would dissipate quickly up into the atmosphere as it is lighter than air—unlike gasoline, which in the event of a leak or accident pools on the ground and creates a cloud of evaporated fuel that is easily ignited. Natural gas has a high ignition temperature, about 1,200° F, compared with about 600° F for gasoline. While fires or even explosions could occur, overall the safety of CNGVs should be no worse than gasoline vehicles and is likely to be better.

2.7.3 Emissions

Compared with vehicles fueled with conventional diesel and gasoline, natural gas vehicles can produce significantly lower amounts of harmful emissions such as particulate matter and hydrocarbons. Natural gas has a higher ratio of hydrogen to carbon than gasoline, reducing CO_2 emissions for the same amount of fuel consumed. However, methane is a potent greenhouse gas, so it is important to prevent methane leakage throughout the well-to-wheels life cycle if the greenhouse gas benefits of natural gas are to be realized, as discussed in Chapter 3.

2.7.4 Vehicle Costs and Characteristics

Other than the tank, CNGVs do not require significant re-engineering from their gasoline counterparts, although the cylinder head and pistons must be redesigned for a higher compression ratio and the ignition system modified. These design costs are significant for low volume production, but should be almost zero at high-volume. The lower density of the fuel means that CNG engines have lower output than gasoline engines of the same size, though this is mitigated to some extent by the higher compression ratios possible with the high octane of the fuel. For the analysis in this report, CNGVs are assumed to operate with the same efficiency as gasoline-powered vehicles, including future efficiency improvements. CNG engines were assumed to be 10 percent larger than other ICE engines for the purpose of calculating engine cost at the same power output.

TABLE 2.8 Comparison of the Honda Civic NG with Similar Vehicles

	Civic NG	Civic LX	Civic Hybrid
MSRP[a]	$26,805	$18,505	$24,200
mpg	27/38	28/39	44/44
Fuel cost	$1,050	$1,800	$1,300
Power	110 HP	140 HP	110 HP
Cargo (cubic feet)	6.1	12.5	10.7
Weight (pounds)	2848	2705	2853
CO_2 (grams/mile)	227	278	202

[a] Manufacturer's suggested retail price.

SOURCE: American Honda Motor Company; available at http://www.honda.com/.

CNGV vehicles currently are sold in very low volumes and, partly due to that, cost significantly more than their gasoline-powered counterparts. For example, the base price of the 2012 Honda Civic NG vehicle is about $8,000 more than a similarly equipped Civic LX. Table 2.8 compares the 2012 Honda Civic NG with the LX and the Civic Hybrid.

The CNGV has higher up-front vehicle costs mainly because its high-pressure storage tanks are bulky and expensive. Currently, a CNGV might require nearly ten years to recover the higher purchase price, but these costs should come down significantly as production volume increases. The large fuel tank also reduces vehicle interior space, especially in the trunk. CNGVs could also be built as hybrids with the same incremental cost and benefits as gasoline HEVs.

2.8 SUMMARY OF RESULTS

The previous sections present a variety of options for reducing oil use and GHG emissions in LDVs and a methodology for estimating how much might be accomplished by 2050. This section summarizes those results. An example of how one vehicle might evolve illustrates how the benefits and costs were determined. This is followed by a series of tables showing the technology results that were input into the energy audit model, the results of those analyses, and the data that was input to the scenario models discussed in Chapter 5. Detailed results can be found in Appendix F.

2.8.1 Potential Evolution of a Midsize Car Through 2050

As an illustration of how a vehicle might evolve with increasing fuel economy technology, this section examines a midsize car, one of the six vehicles the committee analyzed.

Both a conventional drivetrain and a hybrid electric drivetrain are traced from a baseline 2007 vehicle to a 2050 advanced vehicle. Similar information for a BEV and FCEV and for the other vehicle types is shown in Appendix F. This evolution assumes that there is continuous pressure (from either or both regulatory pressure and/or market forces) to improve fuel economy and reduce emissions of greenhouse gases.

Table 2.9 shows details of the evolution of the vehicle with a conventional drivetrain. As can be seen in the table, the combination of shifting to a downsized turbocharged direct injection engine with high EGR and an advanced 8-speed automatic transmission drastically reduces pumping losses within the engine and, to a lesser extent, reduces friction losses and increases indicated thermal efficiency. The combination of idle-off and an advanced alternator allow fuel use during idling to be virtually eliminated. In addition, engine efficiency at low loads can be improved by increasing the charging rate of the alternator to the battery, thereby storing the energy for later use and allowing the engine to operate at more efficient load levels. In addition, smart alternators can improve the capture of regenerative braking energy. There are also improvements in transmission and torque converter efficiency and reductions in accessory loads.

The overall result in both the 2030 mid-level and optimistic case is nearly a 50 percent increase over the EPA 2-cycle tests in overall brake thermal efficiency, and a similar increase in fuel economy (50.5 mpg for the mid-level case) with no changes in vehicle loads. With load reduction, 2030 fuel economy levels of nearly 66 mpg (mid) and 75 mpg (optimistic) are possible without full hybridization. The added benefits of the vehicle load reduction—in particular, the weight reduction, which pays back about 6 to 7 percent fuel economy improvement for every 10 percent reduction in weight—are quite powerful.

By 2050, strong additional benefits can be gained by further vehicle load reductions and, within the drivetrain, primarily by continued improvements in indicated efficiency and reductions in friction losses. Improvements in the transmission and torque converter are minor because most of the possible improvements have been done by 2030, but some further reduction in pumping losses and improvements in accessories is possible. Successful achievements of these improvements can yield startling levels of fuel economy—88.5 mpg for the mid-level case, and 111.6 mpg for the optimistic case. Note that these estimates are for the EPA test cycle, and on-road results will be significantly lower.

Table 2.10 tracks the evolution of the benefits of adding a hybrid drivetrain to the technologies already onboard the advanced conventional vehicles. Note that part of the "standard" benefits of hybrid drivetrains are already captured by the combination of stop-start and advanced alternators in the conventional vehicles. While the hybrid system allows elimi-

TABLE 2.9 Details of the Potential Evolution of a Midsize Car, 2007-2050

Conventional Drivetrain	Baseline	2030 Midrange	2030 Optimistic	2050 Midrange	2050 Optimistic
Engine type	Baseline	EGR DI turbo	EGR DI turbo	EGR DI turbo	EGR DI turbo
Engine power, kW	118	90	84	78	68
Transmission type	6-sp auto	8-sp auto	8-sp auto	8-sp auto	8-sp auto
Drivetrain improvements					
Brake energy recovered through alternator, %	—[a]	14.1	14.1	14.1	14.1
Reduction in transmission losses, %	n/a	26	30	37	43
Transmission efficiency, %	87.6	91	91	92	93
Reduction in torque converter losses, %	n/a	69	75	63	88
Torque converter efficiency, %	93.2	98	99	99	99
Reduction in pumping losses, %	n/a	74	76	80	83
Reduction in friction losses, %	n/a	39	44	53	60
Reduction in accessory losses, %	n/a	21	25	30	36
% increase in indicated efficiency	n/a	5.6	6.5	10.6	15.6
Indicated efficiency, %	36.3	38.4	38.7	40.2	42
Brake thermal efficiency, %	20.9	29.6	30.3	32.5	34.9
Load changes					
% reduction in CdA	n/a	15	24	29	37
CdA (m^2)	7.43	6.31	5.64	5.29	4.68
% reduction in Crr	n/a	23	31	37	43
Crr	0.0082	0.0063	0.0057	0.0052	0.0047
% reduction in curb weight	n/a	20	25	30	40
Curb weight, lb	3325	2660	2494	2328	1995
Fuel economy, test mpg	32.1	65.6[b]	74.9	88.5	111.6

NOTE: All conventional drivetrains have stop-start systems and advanced alternators that can capture energy to drive accessories.

[a] Ricardo assumed stop start and smart alternator, with 14.1 percent of braking energy recovered, resulting in fuel economy = 34.9 mpg.

[b] Fuel economy with drivetrain changes only = 50.5 mpg.

TABLE 2.10 Details of the Potential Evolution of a Midsize Car Hybrid, 2007-2050

Hybrid Drivetrain—P2 hybrid with DCT8 transmission	2030 mid	2030 opt	2050 mid	2050 opt
Engine power, kW	88	82	77	68
Drivetrain improvements				
% additional pumping loss reduction[a]	80	80	80	80
% additional friction loss reduction[a]	30	30	30	30
% tractive energy provided by regen	20	22	24	26
Brake thermal efficiency, %	33.7	34.3	36.3	38.5
% of waste heat recovered	0	0	1	2
Fuel economy, test mpg	81.7[b]	95.1	115.8	150.9
Hybrid benefit over conventional, %	25	27	31	35

[a] Additional from conventional drivetrain in that year.

[b] Fuel economy with drivetrain changes only = 62.6 mpg.

nation of most pumping losses, the actual overall efficiency improvement is modest as pumping losses were already reduced to low levels in the conventional ICE case. Most of the incremental efficiency gains from the hybrid system are due to the tractive energy provided by capture of regenerative braking energy.

As shown in Table 2.10, the overall hybrid fuel economy benefit over the corresponding conventional drivetrain vehicle increases from 25 to 27 percent in 2030 to 31 to 35 percent in 2050; however, the hybrid benefit in terms of actual fuel consumption actually declines in the future—from about 0.30 gallons per 100 miles for the 2030 mid-level case to 0.23 gallons per 100 miles in the 2050 optimistic case. In other words, as non-hybrid ICEVs grow more efficient, the actual fuel savings and monetary benefit of hybridization may decline even as hybrid systems improve. For example, as vehicle mass decreases, the potential energy savings from regenerative braking also decreases.

An interesting aspect of the evolution of hybrids is the improvement in the efficiency of electric components, not shown in the table but included in the fuel economy calculations. For example, the benefits of hybridization will increase with improvements in electric motor/generator efficiency, battery in/out efficiency, and improving control strategies as onboard computer power increases over time. Note that these benefits also apply to BEVs and FCVs. Also, the 2050 hybrids benefit from waste heat recovery.

2.8.2 Technology Results, Performance, and Costs

Tables 2.11 and 2.12 and Figures 2.8 through 2.11 summarize the results from the committee's vehicle analyses. Note that fuel consumption was directly assessed only for 2030 and 2050. Between 2010 and 2030 and between 2030 and 2050, fuel consumption was assumed to have a constant multiplicative reduction each year.

Table 2.11 presents the load reductions assessed by the committee. These reductions were applied consistently to the calculations of costs and benefit for all of the technology types. Note that "Trucks" in this table is the sales-weighted average of unibody and body-on-frame light trucks from Table 2.2.

Table 2.12 presents the overall fuel economy calculated by the committee for the average car and light truck of each type. It is presented in miles per gallon because that is the metric usually used in the United States. There are three caveats with the numbers in Table 2.12. First, at very high mpg levels, large changes in mpg are needed to have much impact on fuel consumption (see Figure 2.1 for an illustration of this effect). Second, Table 2.12 shows the mpg results of the test cycles which do not include the adjustment for real-world fuel consumption. Third, the BEV and FCEV numbers are for the vehicle and do not account for the energy needed to produce the electricity or hydrogen. This is especially important for BEVs, where there are substantial losses in electricity generation. Chapter 3 adds assessments of upstream energy losses.

Figures 2.8 through 2.11 present the incremental cost calculated for each of the technology types. Note that these costs are all incremental to a baseline 2010 conventional vehicle. They are also direct manufacturing costs to the manufacturer.

TABLE 2.11 Load Reduction, Percent Relative to 2010

	Rolling Resistance		Aerodynamic Drag		Mass	
	Cars	Trucks	Cars	Trucks	Cars	Trucks
2030 Midrange	26%	15%	18%	15%	20%	18%
2030 Optimistic	40%	30%	31%	29%	30%	27%
2050 Midrange	33%	23%	26%	24%	25%	23%
2050 Optimistic	46%	37%	39%	37%	40%	37%

TABLE 2.12 Estimated Miles per Gallon Gasoline Equivalent (mpgge) on EPA 2 Cycle Tests

	ICEV		HEV		BEV		FCEV	
	Cars	LT	Cars	LT	Cars	LT	Cars	LT
2010 Baseline (mpgge)	31	24	43	32	144	106	89	65
2030 Midrange (mpgge)	64	46	78	54	190	133	122	86
2050 Midrange (mpgge)	87	61	112	77	243	169	166	115
2030 Optimistic (mpgge)	74	52	92	64	219	154	145	102
2050 Optimistic (mpgge)	110	77	146	100	296	205	206	143

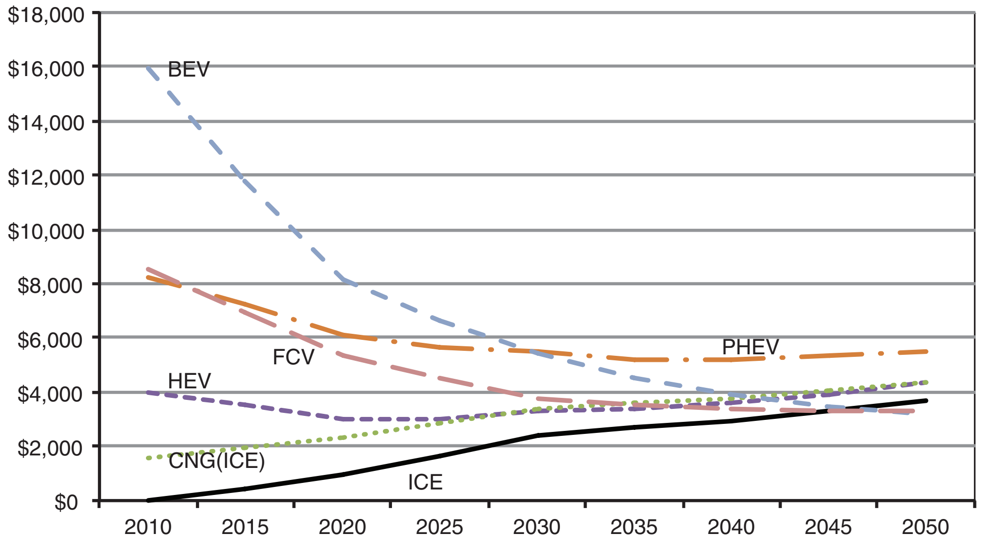

FIGURE 2.8 Car incremental cost versus 2010 baseline ($26,341 retail price)—Midrange case.

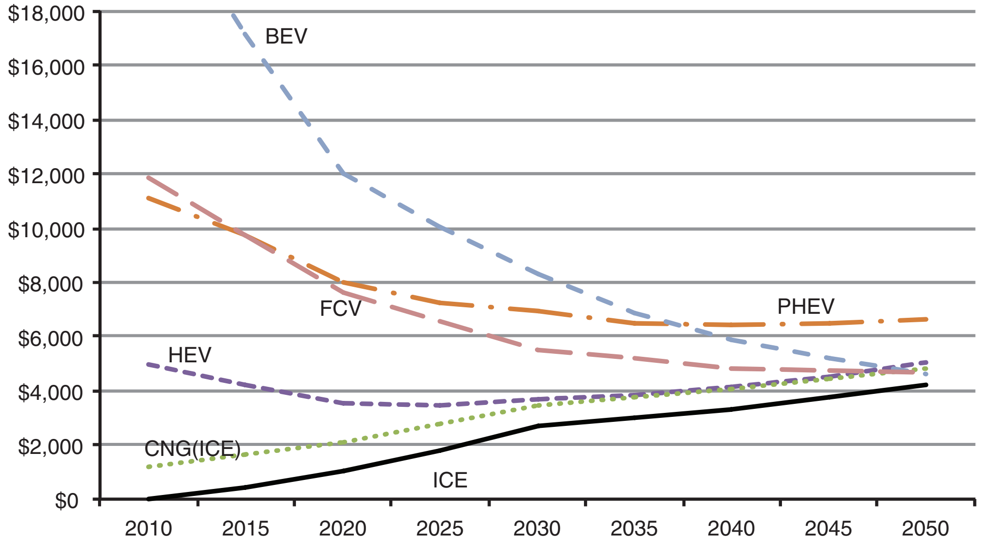

FIGURE 2.9 Light truck incremental cost versus 2010 baseline ($32,413 retail price)—Midrange case.

Markups for retail prices are evaluated in Chapter 5. Finally, the cost estimates assume that high volume production has already been realized. While this is not realistic for BEV, PHEV, and FCEV production in the near term, it allows all technologies to be evaluated on a consistent basis. Cost increases for near term, lower volume production are incorporated into the modeling in Chapter 5.

2.9 COMPARISON OF FCEVs WITH BEVs

FCEVs and BEVs are electric vehicles having no tailpipe GHG emissions. Both are "fueled" by an energy carrier (electricity or hydrogen) that can be produced from a myriad of traditional and renewable energy sources (biofuels, natural gas, coal, wind, solar, hydroelectric, and nuclear). Three primary considerations differentiate their prospects for introduction and acceptance as LDVs: vehicle attributes, rate of technology development, and infrastructure:

- *Vehicle attributes.* FCEVs provide the full utility of current on-road vehicles. BEVs, however, require time consuming "refueling" (recharging) and only offer limited driving range between "refuelings."
- *Rate of technology development.* A key requirement for realization of projected technology advances for battery and fuel cell systems is the continued dedication of research and development resources. Because demand for improved battery technologies is driven

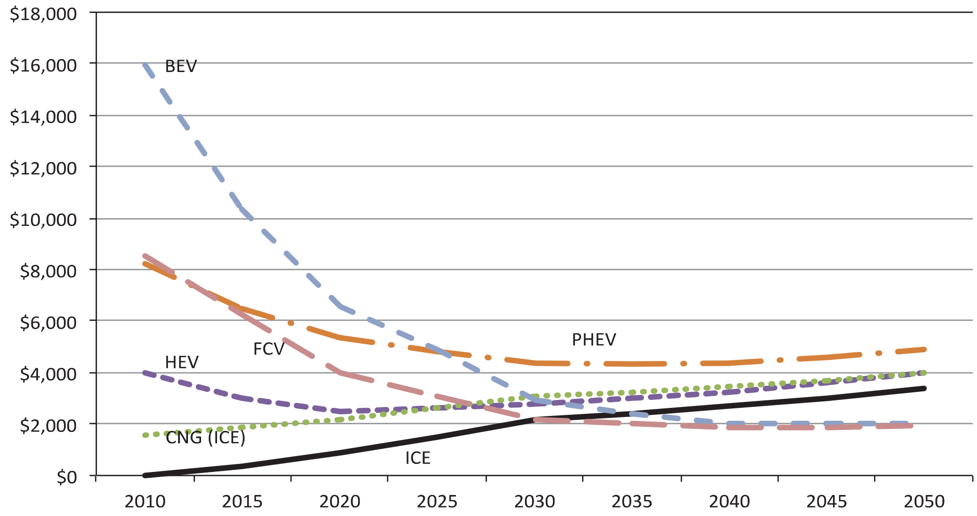

FIGURE 2.10 Car Incremental cost versus 2010 baseline ($26,341 retail price)—Optimistic case.

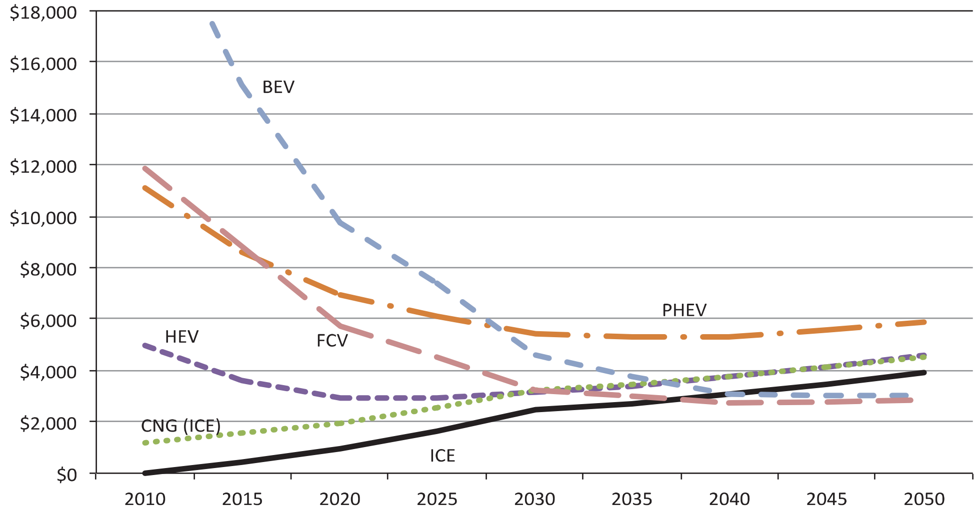

FIGURE 2.11 Light truck incremental cost versus 2010 baseline ($32,413 retail price)—Optimistic case.

by their established application in portable communication/computer devices, prospects for short-term return on R&D investments are substantial.

- *Infrastructure* is discussed in Chapter 3, but it should be noted that the barriers facing hydrogen are more formidable than those facing electricity. A brand new infrastructure for producing and distributing hydrogen would have to be built in concert with FCEV manufacturing. Neither is viable without the other, and the investments required both for manufacturing vehicles and hydrogen are extremely large. Both industries would require guarantees that the other will produce as promised, and that probably will entail a government role.

2.10 FINDINGS

- Large increases in fuel economy are possible with incremental technology that is known now for both load reduction and drivetrain improvements. The average of all conventional LDVs sold in 2050 might achieve EPA test values of 74 mpg for the midrange case and 94 mpg for the optimistic case. Hybrid LDVs might reach 94 mpg for the midrange case and 124 mpg for the optimistic case by 2050. On-road fuel economy values will be significantly lower.
- To obtain the efficiencies and costs estimated in this chapter, manufacturers will need incentives or regu-

latory standards, or both, to widely apply the new technologies.

- The unit cost of batteries will decline with increased production and development; additionally, the energy storage (in kWh) required for a given vehicle range will decline with vehicle load reduction and improved electrical component efficiency. Therefore battery pack costs in 2050 for a 100-mile real-world range are expected to drop by a factor of about 5 for the midrange case and at least 6 for the optimistic case. However, even these costs are unlikely to allow a mass-market vehicle with a 300-mile real-world range. In addition to the weight and volume requirements of these batteries, they are unlikely to be able to be recharged in much less than 30 minutes. Therefore BEVs may be used mainly for local travel rather than as all-purpose vehicles.
- BEVs and PHEVs are likely to use Li-ion batteries for the foreseeable future. Several advanced battery technologies (e.g., lithium-air) are being developed that would address some of the drawbacks of Li-ion batteries, but their potential for commercialization by 2050 is highly uncertain and they may have their own disadvantages.
- PHEVs offer substantial amounts of electric-only driving while avoiding the range and recharge time limitations of BEVs. However, their larger battery will always entail a significant cost premium over the cost of HEVs, and their incremental fuel savings will decrease as the efficiency of HEVs improves.
- The technical hurdles that must be surmounted to develop an all-purpose vehicle acceptable to consumers appear lower for FCEVs than for BEVs. However, the infrastructure and policy barriers appear larger. Well before 2050, the cost of FCEVs could actually be lower than the cost of an equivalent ICEV, and operating costs should also be lower. FCEVs are expected to be equivalent in range and refueling time to ICEVs.
- Making CNG vehicles fully competitive will require building large numbers of CNG fueling stations, moving to more innovative tanks to extend vehicle range and reduce the impacts on interior space, and developing manufacturing techniques to reduce the cost of CNG storage tanks.
- If CNGVs can be made competitive (both vehicle cost and refueling opportunities), they offer a quick way to reduce petroleum consumption, but the GHG benefits are not great.
- Codes and standards need to be developed for the vehicle-fueling interface.
- International harmonization of vehicle safety requirements is needed.
- While fundamental research is not essential to reach the targets calculated in this chapter, new technology developments would substantially reduce the cost and lead time to meet these targets. In addition, continued research on advanced materials and battery concepts will be critical to the success of electric drive vehicles. The committee recommends the following research areas as having the greatest impact:
  —Low-cost, conductive, chemically stable plate materials: fuel cell stack;
  —New durable, low-cost membrane materials: fuel cell stack and batteries;
  —New catalyst structures that increase and maintain the effective surface area of chemically active materials and reduce the use of precious metals: fuel cell stack and batteries;
  —New processing techniques for catalyst substrates, impregnation and integration with layered materials: fuel cell stack and batteries;
  —Energy storage beyond Li-ion: PHEVs and BEVs;
  —Reduced cost of carbon fiber and alternatives to PAN as feedstock;
  —Replacements for rare earths in motors;
  —Waste heat recovery: ICEVs, HEVs, and PHEVs; and
  —Smart car technology.

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3

Alternative Fuels

This chapter discusses the fuel production and use associated with striving to meet the overall study goals of a 50 percent reduction in petroleum use by 2030 and an 80 percent reduction in petroleum use and in greenhouse gas (GHG) emissions from the light-duty vehicle (LDV) fleet by 2050 compared to the corresponding values in 2005. It addresses the primary sources of energy for making alternative fuels, the costs of alternative fuels, and the investment needs and the net GHG emissions of the fuels delivered to the LDV fleet over time. Alternative fuels are transportation fuels that are not derived from petroleum, and they include ethanol, electricity (used in plug-in electric vehicles [PEVs] such as plug-in hybrid electric vehicles [PHEVs] or battery electric vehicles [BEVs]), hydrogen, compressed or liquid natural gas, and gasoline and diesel derived from coal, natural gas, or biomass. Petroleum-based fuels are liquid fuels derived from crude oil or unconventional oils.

The chapter opens with a summary discussion of the study goals, fuel pathways, trends in the fuels market, fuel costs, investment costs, and GHG emissions for an LDV in 2030 using each fuel, and it includes a summary table for each of the last three categories, as well as some cross-cutting findings. More detailed discussions of each fuel follow the summary discussion, with a section devoted to each fuel. Also discussed are carbon capture and storage, and resource needs and limitations.

3.1 SUMMARY DISCUSSION

3.1.1 The Scope of Change Required

The study goals are aggressive and require significant improvements to the vehicle and the fuel system to meet the desired goals. The number of LDVs and the vehicle miles traveled (VMT) are expected to nearly double from 2005 to 2050, adding challenges to meeting the goals.[1] To reach the goals with twice as many LDVs on the road in 2050 means that each LDV would consume on average only 10 percent of the petroleum consumed compared to 2005 and emit only 10 percent of the net GHG emissions. Gasoline and diesel made from petroleum would be nearly eliminated from the fuel mix to reach the petroleum reduction goal. The 80 percent net GHG emissions reduction goals can be met by various combinations of lower fuel consumption rate (inverse of fuel economy) and lower fuel net GHG emission (Table 3.1). The higher the reductions in LDV fuel consumption rate, the lower the reductions in fuel net GHG emissions would need to be to reach the GHG reduction goal. As discussed in Chapter 2, LDV fleet economy improvements of 3 to 5 times may be technically feasible by 2050, meaning that the average net GHG emissions of the fuel used in the entire LDV

TABLE 3.1 LDV Fuel Economy Improvement and Fuel GHG Impact Combinations Needed to Reach an 80 Percent Reduction in Net GHG Emissions Compared to 2005 Assuming a Doubling in Vehicle Miles Traveled (VMT)

LDV Fuel Economy Increase versus 2005	LDV Fuel Consumption Rate Relative to 2005 (percent)[a]	Requisite Reduction in Net Fuel System GHG Impact versus 2005 (percent)[b]
2×	50	80
3×	33	70
4×	25	60
5×	20	50
6×	17	40

[a] The vehicle fuel consumption rate (e.g., gal/100 mi) corresponding to a given increase in fuel economy (e.g., miles per gallon) relative to the base year level. For example, a quadrupling (4×) of fuel economy simply means that the fuel consumption rate is 25 percent of the base level.

[b] The net reduction of system-wide GHG emissions from fuel supply sectors needed to meet an LDV sector-wide 80 percent GHG reduction goal for a given fuel economy gain when assuming a fixed doubling of VMT, that is, without accounting for induced effects such as VMT rebound due to higher fuel economy.

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[1] The EIA *Annual Energy Outlook 2011* (EIA, 2011a) is the basis for these projections.

fleet would have to be reduced by 50 to 70 percent per gallon of gasoline equivalent (gge) by that time.

Finding: Meeting the study goals requires a massive restructuring of the fuel mix used for transportation. Petroleum-based fuels must be largely eliminated from the fuel mix. Other alternative fuels must be introduced such that the average GHG emissions from a gallon equivalent of fuel are only about 40 percent of today's level.

3.1.2 Fuel Pathways

Many different alternative fuel pathways have been proposed, and this study selected seven different fuel pathways to analyze: conventional petroleum-based gasoline, biofuels (including ethanol and "drop-in"[2] biofuels), electricity, hydrogen, compressed natural gas (CNG), gas to liquids (GTL), and coal to liquids (CTL). These were selected because of their potential to reduce petroleum use, to be produced in large quantities from domestic resources, and to be technically and commercially ready for deployment within the study period. Most fuels selected have lower net GHG emissions than petroleum-based fuels. Other alternative-fuel pathways were discussed but not included for detailed analysis because they did not meet the first three criteria. For example, methanol is discussed in Appendix G.8 but was not included for detailed analysis because of environmental and health concerns that inhibit fuel distribution and retail companies from broadly offering methanol as a fuel.

The fuel costs, net GHG emissions, investment needs, and resource requirements were analyzed on a consistent basis for the different fuels to facilitate comparisons among fuels. Future technology and cost improvements for the selected fuels are considered and compared on a consistent basis, even though the extent of improvement for different fuels is likely to vary.

3.1.3 Developing Trends in the Fuels Market

Several developments in the energy markets over the past few years will have large impacts on long-term LDV fuel-use patterns. First, the fuel economy of the LDV fleet will increase rapidly over the next decade because of higher Corporate Average Fuel Economy (CAFE) standards effective through 2016 and proposed through 2025. The CAFE standards increase requirements from 23.5 mpg in 2010 to 34.1 mpg in 2016 to 49.7 mpg in 2025. Alternative fuels and new LDV technologies would compete with future gasoline or diesel LDVs that use much less petroleum and have lower net GHG emissions. From a consumer viewpoint, the decreasing volume of gasoline needed to travel a mile reduces the economic motivation to switch from gasoline to an alternative fuel.

Second, biofuel production is expected to increase as a result of the Renewable Fuel Standard 2 (RFS2) passed as part of the 2007 Energy Independence and Security Act (EISA). This legislation mandated the consumption of 35 billion gallons of ethanol-equivalent[3] biofuel and 1 billion gallons of biodiesel (about 24.3 billion gge/yr based on energy content) by 2022. The detailed requirements of RFS2 are discussed in Appendix G.1. Based on the 2010 gasoline use of 136 billion gge/yr (8.88 million bbl/d), this mandate increases biofuel use from 9.9 percent (0.87 million bbl/d) to 18 percent (1.59 million bbl/d) of the gasoline mix by volume (EIA, 2011b). Although the mandated volume for cellulosic biofuel is not expected to be met by 2022, any additional biofuel volume in the conventional gasoline mix reduces the need for gasoline from petroleum and the volume of other alternative fuels needed to reach the study goals. See Section 3.2, "Biofuels," in this chapter for a detailed discussion.

Third, the volume of economic natural gas from shale deposits within the United States has been increasing rapidly. In its June 18, 2009, report the Potential Gas Committee upgraded by 39 percent the estimated U.S. potential natural gas reserves (defined as being potentially economically extractable by the use of available technology at current economic conditions) compared with its previous biannual estimate (Potential Gas Committee, 2009). Based on the new estimates, the probable natural gas reserves would provide about 86 years of consumption if the consumption rate stays at the current level. In 2011, the Potential Gas Committee increased its estimates such that 90 years of probable reserves exist based on 2010 consumption. Many previous studies on alternative fuels did not include natural gas as a possible source for LDV fuel because of limited domestic supply, and the likely price increase in electricity and residential heating costs associated with high natural gas use in the transportation market. With increasing domestic production, natural gas now is a viable option for providing transportation fuels through multiple pathways including electricity, hydrogen, GTL, and CNG. See Section 3.5, "Natural Gas," in this chapter and Appendix G.7 for a detailed discussion.

3.1.4 Study Methods Used in the Analysis

This study considers conventional and alternative fuels for the 2010-2050 period, and this committee undertook a number of tasks to generate possible fuel scenarios and data for use in the modeling efforts described in Chapter 5. The primary sources for the data are different for each fuel and are explained in the sections that provide details on each fuel below in this chapter. The committee made efforts to standardize input data and definitions between the primary

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[2] Drop-in fuel refers to nonpetroleum fuel that is compatible with existing infrastructure for petroleum-based fuels and with LDV ICEs.

[3] A gallon of ethanol has about 77,000 Btu, compared with 116,000 Btu in 1 gallon of gasoline equivalent.

information sources. The tasks the committee performed include:

- Assessed the current state of the technology readiness for each fuel using information gathered from presentations made to this committee and published literature.
- Estimated future improvements to these technologies that could be broadly deployed in the study period.[4]
- Estimated the range of costs based on future technology for each fuel delivered to the LDV at a fueling station in a similar way for each fuel. The reference price basis in the Energy Information Administration's (EIA's) *Annual Energy Outlook 2011* (EIA, 2011a) is used for all primary fuel prices. Investment costs are expressed in 2009 dollars.
- Estimated the initial investment costs needed to build the infrastructure for each fuel pathway.[5]
- Estimated the net GHG emissions per gallon of gasoline-equivalent for each fuel based on the methods selected for producing the fuel. An upstream GHG component, a conversion component, and a combustion component were included in the estimate of net GHG emissions.

3.1.5 Costs of Alternative Fuels

The costs of alternative fuels through 2035 are estimated based on the energy raw material prices in the reference case of the *Annual Energy Outlook 2011* (AEO; EIA, 2011a), and the basis and assumptions for the estimates are explained in the individual fuel sections. Fuel prices beyond 2035 were estimated by the committee. Table 3.2 summarizes the expected alternative fuel costs for 2030 on a \$/gge or \$/kWh basis for some of the fuel pathways and shows the consumer's annual fuel costs for a new vehicle of that type based on 2030 estimated vehicle mileage.

While the values in Table 3.2 are useful guideposts for this analysis, there are a few factors to keep in mind. First, the fuel costs shown in Table 3.2 are untaxed—current or future taxes are not included and could alter the actual annual cost that consumers pay. Second, the per-gallon of gasoline-equivalent fuel cost estimates in 2030 are a snapshot in time and will likely change as technology develops and world energy prices change. Third, the untaxed fuel-purchase costs to consumers each year appear similar for most fuels except for CNG and the BEV, which are significantly lower than others. Given the small separation for the other options in 2030, untaxed fuel costs are not expected to be a significant driving force for consumers to switch from gasoline to alternate vehicle technologies in this timeframe. Untaxed fuel cost differences of only several hundred dollars per year will not cover the additional vehicle costs described in Chapter 2.[6]

TABLE 3.2 2030 Annual Fuel Cost per LDV, Untaxed Unless Noted

Fuel	Fuel Cost ($/gge or kWh)	Annual Consumer Use (gge or kWh)	Annual Consumer Fuel Cost ($/yr)
Gasoline (taxed)	3.64/gge	325 gge	1,183
Biofuel (drop in)	3.39/gge	325 gge	1,102
Gasoline (untaxed)	3.16/gge	325 gge	1,027
PHEV10[a]	3.16/gge 0.141/kWh	260 gge 650 kWh	913
CTL with CCS	2.75/gge	325 gge	894
GTL	2.75/gge	325 gge	894
PHEV40[b]	3.16/gge 0.175/kWh	130 gge 1,950 kWh	752
Hydrogen—CCS case	4.10/gge	165 gge	676
Natural gas—CNG	1.80/gge	325 gge	585
BEV	0.143/kWh	3,250 kWh	465

NOTE: All fuel costs are based on the 2011 AEO (EIA, 2011a) for 2030. The assumed fuel economies are representative of on-road LDV averages for 2030 described in the scenarios in Chapter 5. The following assumptions were made: 13,000 mi/yr traveled and 40 mpgge for liquid and CNG vehicles, 80 mpgge for hydrogen and 4.0 mi/kWh for electric vehicles. PHEV10 gets 20 percent of miles on electric, PHEV40 gets 60 percent. All costs are untaxed unless noted. Electricity cost includes the retail price plus amortization of the cost of a home charger.

[a] PHEV10 is a plug-in hybrid vehicle designed to travel about 10 miles primarily on battery power only before switching to charge-sustaining operation.

[b] PHEV 40 is a plug-in hybrid vehicle designed to travel about 40 miles primarily on battery power only before switching to charge-sustaining operation.

Finding: As the LDV fleet fuel economy improves over time, the annual fuel cost for an LDV owner decreases. With high fleet fuel economy, the differences in annual fuel cost between alternative fuels and petroleum-based gasoline decreases and the annual costs become similar to one another. Therefore, over time fuel-cost savings will become less important in driving the switch from petroleum-based fuels to other fuels.

3.1.6 Investment Costs for Alternative Fuels

The investment costs to build the fuel infrastructure are sizable for all of the alternative fuel and vehicle pathways. In fact, these costs remain among the most important barriers

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[4] Some future technologies that might be developed during the study period are not included for detailed analysis because future efficiencies and costs are not well understood. Examples of this include photoelectrochemical hydrogen production and biofuels from algae.

[5] Investment costs are explained in Appendix G.2, "Infrastructure Initial Investment Cost."

[6] As pointed out in Chapters 4 and 5, consumers tend to value about 3 years worth of fuel savings when making decisions on initial vehicle purchases. Using the numbers in Table 3.2, 3 years of untaxed hydrogen saves only \$1,501 compared with taxed gasoline during 2030. The cost saved is not enough to cover the higher cost of a fuel cell electric vehicle (FCEV).

to rapid and widespread adoption of alternatives. Table 3.3 shows the investment costs on a $/gge per day basis and on a $/LDV basis. This calculation includes only the investment in building a new form of infrastructure needed to make and deliver the fuel to the customer. It does not include investment to expand an already large and functioning infrastructure associated with producing more of the basic resource. For instance, for hydrogen made from natural gas, the investment cost includes the cost of converting natural gas to hydrogen, pipelines to deliver the hydrogen, and the full cost of a hydrogen station, but it does not include investments to produce natural gas or deliver it to a plant. A complete list of which costs are included or excluded is shown in Appendix G.2 "Infrastructure Initial Investment Cost." Details for these investment costs are found in the individual fuel sections below in this chapter.

The investment cost for a new petroleum refinery is included in Table 3.3 for perspective. However, with increasing fuel economy for the LDV fleet, no new refinery capacity will be needed during the study period. So in effect the initial investment cost for gasoline is near zero. The alternative-fuel-producing industry, in 2030, must make a $1,000 to $3,000 investment for each new alternative-fuel LDV, whereas almost none is needed for new petroleum gasoline LDVs. This cost differential is a major barrier to large-scale deployment of alternative fuels.

The scale, pace, and modularity of the infrastructure investments vary for the different vehicles and fuels. These differences are noted in the right-most column of Table 3.3. Two basic categories are used to describe the infrastructure requirements: centralized and distributed. Centralized infrastructure investments are those that are borne by a select number of decision makers. For example, the infrastructure for CTL, GTL, or gasoline requires large-scale plants (which cost billions of dollars each) that individual companies would pay for. Biofuels require large-scale investments for biorefineries. Hydrogen requires hydrogen production plants plus smaller-scale distributed investments by retailers to install new storage tanks and fuel pumps. The investment costs for BEVs and PHEVs in Table 3.3 include only the costs for home, workplace, and public chargers. The centralized infrastructure for CNG has already been built, and so the incremental CNG infrastructure costs include home fueling systems (paid for by car owners), or new filling stations (paid for by retailers). Thus, the infrastructure requirements vary from a few very large, multibillion-dollar investments (e.g., for biorefineries) made by a few decision makers in industry, to millions of small multithousand-dollar investments made by millions of decision makers such as consumers, ratepayers, and retailers.

Finding: The investment cost for a new fuel infrastructure using electricity, biofuels, or hydrogen is in the range of $2,000 to $3,000 per LDV. This is a significant barrier to large-scale deployment when compared with an infrastructure cost for using petroleum of only about $530 per LDV.

3.1.7 GHG Emissions from the Production and Use of Alternative Fuels

Operational and infrastructure costs (as noted in Tables 3.2 and 3.3) are critical factors to consider for deployment. However, the net GHG emissions for the different vehicle and fuel options need to be examined to determine how the goal of 80 percent GHG reduction could be met. The estimates of annual GHG emissions in 2030 for different vehicle and fuel options are shown in Table 3.4.

Each vehicle and fuel option has a range of net annual GHG emissions because GHG emissions depend on how the fuels are produced. The range of net GHG emissions for biofuels is large because the net GHG emissions depend

TABLE 3.3 2030 Fuel Infrastructure Initial Investment Costs per Vehicle

Alternative Fuel	2030 Investment Cost	LDV Fuel Use per Day	Infrastructure Investment Cost ($/vehicle)	Cost Burden
Electricity BEV	$330/kWh per day	8.9 kWh	2,930	Distributed (car owners, ratepayers)
Electricity (PHEV40)	$530/kWh per day	5.4 kWh	2,880	Distributed (car owners, ratepayers)
Biofuel (thermochemical)	$3,100/gge per day	0.89 gge	2,760	Centralized (industry)
CTL (with CCS)	$2,500/gge per day	0.89 gge	2,220	Centralized (industry)
Hydrogen (with CCS)	$3,890/gge per day	0.45 gge	1,750	Centralized (industry) and distributed (retailers)
GTL	$1,900/gge per day	0.89 gge	1,690	Centralized (industry)
Natural gas—CNG	$910/gge per day	0.89 gge	810	Distributed (retailers and car owners)
Electricity (PHEV10)	$370/kWh per day	1.75 kWh	650	Distributed (car owners, ratepayers)
Gasoline (new refinery—if needed)	$595/gge per day	0.89 gge	530	Centralized (industry)

NOTE: Basis: 13,000 mi/yr and 40 mpgge for liquid and natural gas vehicles, 80 mpgge for hydrogen, and 4.0 mi/kWh for electric vehicles. PHEV10 gets 20 percent of miles on electric; PHEV40 gets 60 percent. Investment costs are explained in the individual fuel sections.

TABLE 3.4 Estimates of 2030 Annual Net GHG Emissions per Light-Duty Vehicle Used in the Modeling in Later Chapters

Fuel	Net GHG Emissions (kg CO_2e)	Annual Use	Annual GHGs Emissions per LDV (kg CO_2e)	
CTL with CCS	12.29/gge	325 gge		4,000
GTL	11.47/gge	325 gge		3,730
Gasoline	11.17/gge	325 gge		3,630
PHEV10	0.590/kWh	650 kWh	380	3,290
	11.17/gge	260 gge	2,910	
Natural gas	9.20/gge	325 gge		2,990
PHEV40	0.590/kWh	1,950 kWh	1,146	2,600
	11.1/gge	130 gge	1,454	
Hydrogen—low cost	12.2/gge	165 gge		2,010
BEV—reference grid	0.590/kWh	3,250 kWh		1,920
Biofuel—with ILUC[a]	5.0/gge	325 gge		1,620
BEV—low-GHG grid	0.317/kWh	3,250 kWh		1,030
Biofuel—without ILUC	3.2/gge	325 gge		1,040
Hydrogen—with CCS	5.1/gge	165 gge		840
Hydrogen—low-GHG case	2.6/gge	165 gge		430
Biofuel—with ILUC,CCS	–9.0/gge	325 gge		–2925

[a] Indirect land-use changes (ILUC) can have large impacts on net GHG emissions but can vary considerably.

Basis: 13,000 mi/yr and 40 mpgge for liquid and NGVs, 80 mpgge for hydrogen and 4.0 miles/kWh for electric vehicles. PHEV10 gets 20 percent of miles on electric; PHEV40 gets 60 percent. GHG estimates are explained in the individual fuel sections.

on many factors, including the type of feedstock used,[7] the management practices used to grow biomass (e.g., overuse of nitrogen fertilizer could increase N_2O flux), any land-use changes associated with feedstock production,[8] and the use of carbon capture and storage (CCS) with biofuel production. The range of differences for a BEV is determined by the average GHG emissions of the grid and over time may be quite different than shown in Table 3.4. Hydrogen has a large range of possible GHGs determined by the several different choices of production method.

The net GHG emissions from the three typical alternative fuels—biofuels, hydrogen, and electricity—can be either high or low depending on technology choices, carbon costs, regulations, and other factors. Choices driven by technology, economics, and policy determine the GHG emissions for future alternative fuels.

Finding: The GHG emissions from producing biofuels, electricity, and hydrogen can vary depending on the basic resource type and conversion methods used. Making these fuels with methods involving very low GHG emissions increases the technical and cost hurdles, especially during the introductory period. Actions to encourage the use of these more challenging methods should be timed to coincide with large-scale deployment and not be a burden during the introductory period for the fuel. Needed policy actions for each fuel pathway are listed in Appendix G.3.

3.2 BIOFUELS

3.2.1 Current Status

Biofuel is a generic term that refers to any liquid fuel produced from a biomass source. A number of different biofuel products (e.g., biobutanol and drop-in biofuels[9]) derived from different feedstocks (e.g., lignocellulosic[10] biomass and algae) have been proposed, but only corn-grain ethanol and biodiesel were produced in commercially relevant quantities in the United States as of the drafting of this report. Ethanol and biodiesel have been of interest because they can be easily synthesized using well-known processes from commercially available agricultural products (such as corn and soybeans in the United States, sugar cane in Brazil, and other oil seeds elsewhere). However, neither ethanol nor biodiesel is fully fungible with the current infrastructure and LDV fleet designed for petroleum-based fuels.

Ethanol and biodiesel are usually shipped separately and blended into the fuel at the final distribution point. Ethanol can be blended into gasoline in various proportions but has only about two-thirds of the volumetric energy content of petroleum-based gasoline. As of 2011, ethanol supplied almost 10 percent by volume of the U.S. gasoline demand (Figure 3.1). Biodiesel, produced via the transesterification of various vegetable oils or animal fats, supplied less than 1 percent of U.S. transportation fuel demand in 2011 (see Figure 3.1). U.S. biodiesel production capacity was about 2.7 billion gal/yr in 2010 (NBB, 2010), but actual production is significantly lower. Biomass can also be used to synthesize drop-in fuels, that is, synthetic hydrocarbons that would be fully fungible with existing infrastructure and vehicles.

The EISA included an amendment to the Renewable Fuel Standard in the Energy Policy Act (EPAct) of 2005. RFS2 mandated an increase of over 200 percent in the use of biofuels between 2009 and 2022. (See Box 1.1 in Chapter 1.) Biofuels, including corn-grain ethanol and biodiesel, currently require government subsidies or mandates to compete economically with petroleum-based fuels. Increases in ethanol consumption can also be limited by the "blend wall"

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[7] Corn-grain ethanol is likely to have different net GHG emissions than cellulosic biofuel.

[8] Uncertainties in GHG emissions from land-use changes are a key contributor to the wide range of estimates for net GHG emissions from biofuels. Some biofuel feedstock such as corn stover would not contribute much to GHG emissions from land-use changes.

[9] Biofuels that are compatible with existing infrastructure and internal combustion engine vehicles (ICEVs) for petroleum-based fuels.

[10] Plant biomass composed primarily of cellulose, hemicellulose, and lignin.

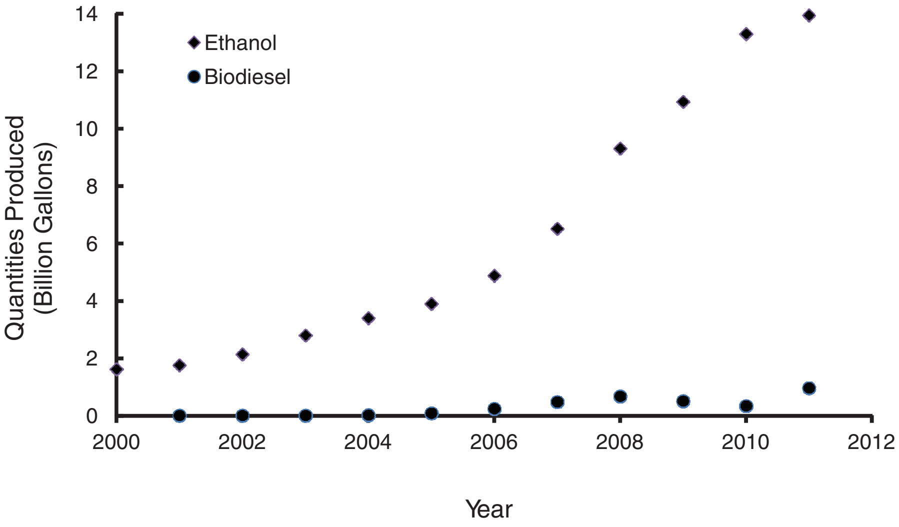

FIGURE 3.1 Amount of fuel ethanol produced in the United States.
SOURCE: Data from EIA (2012b,c).

(NRC, 2011). In 2010, the U.S. Environmental Protection Agency (EPA) approved the use of E15 in internal combustion engine vehicles (ICEVs) of model year 2001 or newer in response to a waiver request by Growth Energy and 54 ethanol manufacturers. Although EPA approved the use of E15 in 2010, its sale just began in July 2012 (Wald, 2012). In April 2012, EPA approved 20 companies for the manufacture of E15 (EPA, 2012a).[11] Without an approved method for eliminating misfueling of older cars,[12] increased ethanol use is likely to be constrained in the near term. In addition, auto manufacturers do not recommend using E15 in any vehicles that were initially designed to use E10 because of concerns that E15 might damage older engines (McAllister, 2012).

Flex-fuel vehicles (FFVs) can use higher concentrations of ethanol (up to 85 percent), and many auto manufacturers produce flex-fuel vehicles because of the CAFE credit[13] they receive (DOE-EERE, 2012c). However, the number of E85 fueling stations is limited (about 2,500 stations across the United States) and varies by state (DOE-EERE, 2012a). The price of E85 has always been higher than petroleum-based gasoline on an equivalent energy content basis.

Although the use of corn-grain ethanol can reduce petroleum imports, its effects on GHG emissions are ambiguous. Life-cycle assessments by various authors have estimated a 0 to 20 percent reduction in GHG emissions from corn-grain ethanol, relative to gasoline (Farrell et al., 2006; Hill et al., 2006; Hertel et al., 2010; Mullins et al., 2010).

The EISA requires the use of additional advanced and cellulosic biofuels that will reduce petroleum imports, lower CO_2e emissions, and be produced predominantly from lignocellulosic biomass. (See Appendix G.1 for definitions of biofuels in EISA.) To qualify as an advanced biofuel, a biofuel would have to reduce life-cycle GHG emissions by at least 50 percent compared with petroleum-based fuels.[14] To qualify as a cellulosic biofuel, a biofuel would have to be produced from cellulose, hemicellulose, or lignin and reduce life-cycle GHG emissions by at least 60 percent compared with petroleum-based fuels. Although RFS2 specified life-cycle GHG reduction thresholds for each type of fuel and EPA makes regulatory determinations accordingly, the actual life-cycle GHG emissions of biofuels could span a wide range (NRC, 2011). Biofuels facilities that began construction after 2007 would have to be individually certified for both biomass source and production pathway to qualify for renewable identification numbers (RINs).[15]

The U.S. government and private investors have invested billions of dollars to develop cellulosic biofuels (see Tables

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[11] When the U.S. Environmental Protection Agency (EPA) approves a new fuel or fuel component, EPA only evaluates the fuel's impact on the emission control system and its ability to meet the evaporative and tailpipe emission standards. EPA does not evaluate the impact of the new fuel on any other aspect of vehicle performance, including degradation of vehicle components and performance that are not associated with the emission control system.

[12] The Renewable Fuels Association submitted a Model E15 Misfueling Mitigation Plan to EPA for review and approval on March 2012. The plan includes fuel labeling to inform customers, a product transfer documentation requirement, and outreach to public and stakeholders. However, those measures will not eliminate the possibility of accidental misfueling.

[13] CAFE credits were used to incentivize vehicle manufacturers to sell large numbers of vehicles that run on natural gas or alcohol fuels. See Chapter 6 for details.

[14] In its *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis* (EPA, 2010b), EPA determined the life-cycle GHG emissions to be 19,200 g CO_2e/million Btu for petroleum-based gasoline and 17,998 g CO_2e/million Btu for petroleum-based diesel.

[15] The Renewable Identification Number (RIN) system was created by EPA to facilitate tracking of compliance with RFS. A RIN is a 38-character numeric code that corresponds to a volume of renewable fuel produced in or imported into the United States.

2.3 and 2.4 in NRC, 2011); however, no commercially viable processes are operational as of the drafting of this report. Initial research focused on cellulosic ethanol; however, the difficulties associated with integrating ethanol into the existing fuel distribution system and the inability to increase ethanol yields to the desired levels have resulted in a shift in research emphasis away from the biochemical conversion processes to the thermochemical or hybrid conversion processes. Conversion processes of lignocellulosic biomass to fuels are discussed below in this chapter.

3.2.2 Capabilities

The production potential of cellulosic biofuels is determined by the ability to grow and harvest biomass and the conversion efficiency of the processes for converting the biomass into a liquid fuel. Many studies have been published, and they show that the currently demonstrated conversion potential is about 46-64 gge/ton of dry biomass feedstock (as summarized in NRC, 2011). This represents an energy-conversion efficiency to liquid fuel of 25 to 50 percent based on the ratio of the lower heating value of the fuel product to that of the biomass feedstock. Much of the balance of the biomass-energy content is used to produce electricity and to power the conversion processes.

3.2.3 Biomass Availability

Multiple potential sources of lignocellulosic biomass can be used to produce biofuels. They include crop residues such as corn stover and wheat straw, fast-growing perennial grasses such as switchgrass and *Miscanthus*, whole trees and wood waste, municipal solid waste, and algae. Each potential source has a production limit. The consumptive water use and other environmental effects of producing biomass for fuels are discussed in detail in *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy* (NRC, 2011).

Several studies have been published on the estimated amount of biomass that can be sustainably produced in the United States (NAS-NAE-NRC, 2009b; DOE, 2011; NRC, 2011, and references cited therein). All of the studies focused on meeting particular production goals and none of them projected biomass availability beyond 2030; they are discussed in Appendix G.4. The studies had different target production dates ranging from 2020 to 2030. The most recent study (DOE, 2011) projected that 767 million tons of additional biomass (above that currently consumed) could be available in 2030 at a farm gate price of less than \$60/ton. This estimate was based on an annual yield growth of 1 percent and would require a shift of 22 million acres of cropland (or 5 percent of 2011 cropland) and 41 million acres of pastureland (or 7 percent of 2011 pastureland) into energy crop production. That amount was assumed to be available in 2050 in this report.

Finding: Sufficient biomass could be produced in 2050, when converted with current biofuel technology and consumed in vehicles with improved efficiencies consistent with those developed by the committee in Chapter 2 (about a factor-of-four reduction in fuel consumption per mile by 2050), that the goal of an 80 percent reduction in annual petroleum use could be met.[16]

3.2.4 Conversion Processes

Several technologies can be used to process biomass into liquid transportation fuels for the existing LDV fleet. Converting corn starch to ethanol and converting vegetable and animal fats to biodiesel or renewable (green) diesel are well-established commercial technologies. As of 2012, the collective capacity of corn-grain ethanol and biodiesel refineries in the United States is sufficient to essentially meet the 2022 RFS2 consumption mandates for conventional biofuels and biomass-based diesel.

There are a number of potential processes for converting cellulosic biomass into liquid transportation fuels. Demonstration facilities have been built for some of the various technologies. Much of the focus on cellulosic biofuel has switched away from ethanol to producing a biofuel that is a drop-in fuel.

Three main pathways are being developed to produce cellulosic biofuels: biochemical, thermochemical, and a hybrid of thermochemical and biochemical pathways. The pathways are discussed in detail in the report *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (NAS-NAE-NRC, 2009b). Briefly, biochemical processes use biological agents at relatively low temperatures and pressures to convert the cellulosic material to biofuels—primarily ethanol and higher alcohols.

Thermochemical conversion uses heat, pressure, and chemicals to break the chemical bonds of the biomass and transform the biomass into many different products. Three main pathways are being considered for thermochemical conversion: gasification followed by Fischer-Tropsch (FT) catalytic processing to make naphtha and diesel, gasification followed by conversion of the syngas into methanol and subsequent conversion into gasoline via the methanol-to-gasoline (MTG) process, and pyrolysis (either high-temperature or lower-temperature hydropyrolysis) followed by hydroprocessing of the pyrolysis oil to produce gasoline and diesel. Other thermochemical pathways are also under development. Thermochemical and biochemical processes can be combined—for example, gasification of the biomass followed by fermentation of the syngas to produce ethanol or other alcohols.

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[16] See Chapter 5 modeling results for further detail.

3.2.5 Costs

The economics of biofuel production have been discussed in a number of studies. Both NAS-NAE-NRC (2009b) and NRC (2011) compared recent information to develop comparative economics. The report *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy* (NRC, 2011) and the references cited therein form the bases for the discussion of economics in this chapter.

Conversion of cellulosic biomass to drop-in biofuels is a relatively new and evolving suite of technologies. Predicting the future developments that can lower the cost of biofuel production is difficult. The cost of production is primarily a function of the cost of biomass, the yield of biofuels, and the capital investment required to build the biofuel conversion facility. Current conversion efficiencies are 46-64 gge/ton of dry biomass (which gives an average value of 55 gge per dry ton with a range of ±9 gge per dry ton).

Current capital costs to build a cellulosic biorefinery vary between 10 and 15 $/gge per year for all of the technologies discussed above. Thus, a biorefinery that would produce 36 million gge/yr consumes about 2,000 dry tons of biomass per day. The biorefinery would cost between $360 million and $540 million to build. An average capital cost would be 12.5 ± 2.5 $/gge per year. Because biorefining is a developing and evolving technology, it is reasonable to assume that yields will increase and that the capital costs will decrease as the technology matures. Yields will increase because of improvements in the catalysts used and in the process configurations. The capital costs are expected to decline primarily because of economies of scale and improvements in the process configurations. Biorefineries that are bigger and more efficient than the first-mover facilities will be built as engineering and construction techniques are refined over time. The analysis is this chapter assumes that yields will increase from a baseline of 55 gge per dry ton in 2012 at a rate of 0.5 percent per year to a yield of 64 gge per dry ton by 2028. The capital costs are assumed to decrease by 1 percent per year through 2050 for an overall reduction in capital cost of 31 percent compared to the present cost. The capital costs given in this report are for fully engineered facilities for a relatively new technology. Others (Wright et al., 2010) have estimated a 60 percent decrease in capital costs as the technology evolves. Figure 3.2 shows the current and future costs to produce cellulosic biofuels based on these assumptions and the assumption that bioenergy feedstock is $75 or $133 per dry ton. Current estimates are for a biomass cost of $75 per ton, but a sensitivity to a higher cost is also included (see Figure 3.2).

Table 3.5 is a summary of projections of cellulosic biofuels that could be available, in addition to the 2012 ethanol and biodiesel production of 14 to 15 billion gal/yr, using different investment rates for new plant capacity. This committee estimated that about 45 billion gge of biofuel would be required to meet the target of 80 percent reduction in petroleum use for the LDV fleet in 2050 and would require about 703 million dry tons per year of biomass feedstock. A uniform annual construction rate of about $10 billion per year can easily produce the projected biofuel needs in 2050. The fuel availabilities are based on the projections discussed

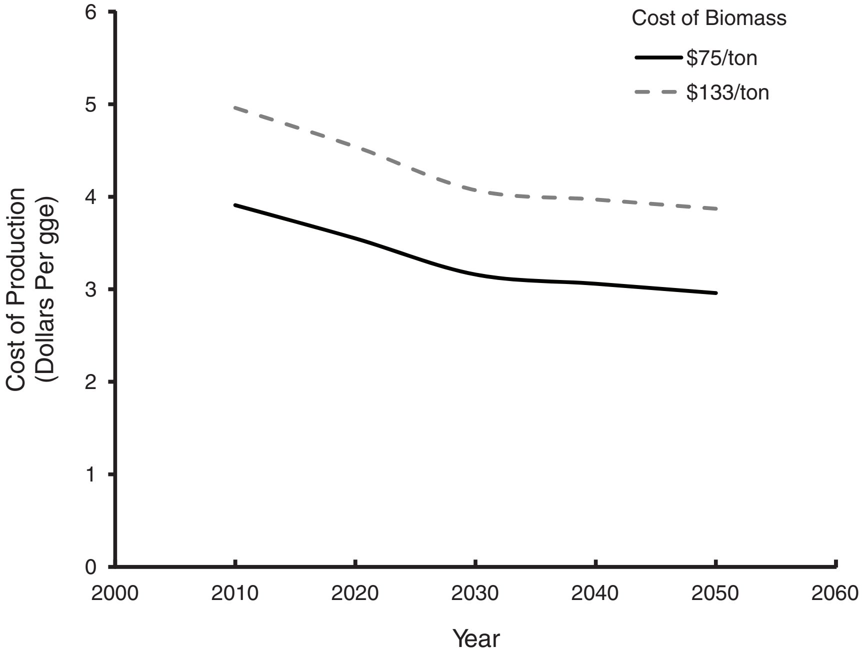

FIGURE 3.2 Sensitivity of biofuel cost to biomass cost.

TABLE 3.5 Estimates of Future Biofuel Availability

	Annual Plant Investment Rate (billion dollars per year)			
	1	4	7.2	10.4
Biofuel production (billion gge per year) by				
2022	0.9	3.7	6.7	9.7
2030	1.8	7.4	13.3	19.2
2050	4.3	17.3	31.2	45.0
Biomass required in 2050 (million dry tons per year)	68	270	488	703
Estimated land-use change (million acres)	5.5	22.2	40.1	57.8
Total investment to 2050 (billion dollars)	38	152	275	396
Average number of biorefineries built per year	2.7	10.8	19.5	28.2

above. Land requirements are scaled from the *U.S. Billion-Ton Update* previously discussed (DOE, 2011).

Worldwide expenditures on exploration and production of petroleum are high (Milhench and Kurahone, 2011). For example, ExxonMobil alone invested over $32 billion globally in capital and exploration projects in 2010. The November 7, 2011, issue of the *Oil and Gas Journal* (2011) reported that the National Oil Companies of the Middle East and North Africa planned to invest a total of $140 billion in oil and natural gas projects in 2012, with even more investments to follow in coming years.

If the biofuels industry grows as projected, many U.S. petroleum refineries will close or be converted to biorefineries. Conversion of a petroleum refinery to a biorefinery will be significantly less costly and labor-intensive than the construction of a "grass-roots" biorefinery.

In all future years, the amount of biofuels that can be produced will most likely be limited not by biomass availability, but rather by the availability of capital to build the biorefineries. However, a potential investor will not start construction without secure contracts for biomass supply and a guaranteed market for the product.[17]

3.2.6 Infrastructure Needs

A large number of biomass conversion facilities would have to be built along with specialized harvesting equipment and a truck fleet to transport the biomass from the fields to the conversion facilities. Economic studies have shown that the conversion facilities need to be near where the crops are grown. Therefore, additional product pipelines would be needed to transport the biofuels from the conversion facilities to the existing petroleum product distribution system. Although drop-in biofuels can use the existing petroleum-product distribution system, feeder lines will most likely be required between the biorefineries and the major petroleum pipelines. However, adding feeder lines will require a relatively small incremental investment.

3.2.7 Regional or Local Effects

Biomass can be grown only in certain parts of the country, and so the conversion facilities will also be located nearby. If drop-in fuels are produced, then the fuels can be shipped via the existing system of petroleum-product pipelines. This system efficiently transports large volumes of petroleum products. Initially, the biofuel refineries will be sited near the locations where the lowest-cost biomass is grown or harvested. Many of these locations are in the Southeast and Midwest United States. The major petroleum pipelines between the Gulf Coast and the Northeast and North Central United States bisect these regions. Tie-ins to these pipeline systems would be relatively short.

3.2.8 Safety

The chemical properties of drop-in cellulosic biofuels will be similar to those of existing, petroleum-based LDV fuels, with no additional fuel-related safety hazards. Truck traffic in rural areas is expected to increase, which could increase traffic accidents in these areas.

3.2.9 Barriers

The primary barrier to displacing petroleum with biofuels is economic. At present, biofuels are more expensive to produce than petroleum-based fuels. The corn-grain ethanol industry had many years of government subsidies and is currently supported by the RFS2 consumption mandate. Subsidies or mandates are projected to be required to support cellulosic biofuel unless the price of oil is close to $190/bbl or conversion costs decline as projected.

As discussed above and in detail in other reports (NAS-NAE-NRC, 2009b; NRC, 2011), ethanol involves definite infrastructure issues. Pure ethanol cannot be used in conventional ICEs because of cold-start problems. It has to be blended with petroleum-based gasoline. The highest content allowed in the United States is 85 percent ethanol by volume (E85). Although E85 could contain up to 85 percent ethanol, its ethanol content typically averages only 75 percent or even less in the winter.

As of 2012, the fuel industry was close to reaching the maximum amount of ethanol that can be consumed by blending into E10. Total U.S. gasoline consumption in 2010 was just over 138 billion gallons. Blending all of this as E10 would consume only 13.8 billion gallons of ethanol, which is

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[17] Factors that can affect actual supply of biomass for fuels are discussed in the report *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy* (NRC, 2011).

less than the 15 billion gallons of conventional ethanol mandated by RFS2. Fewer than 0.1 billion gallons of E85 were sold in 2009. As the fuel economy of vehicles improves and gasoline sales decline, even less gasoline will be available to be blended with the volume of ethanol mandated. Drop-in biofuels do not have this limitation.

3.2.10 GHG Reduction Potential

There is ongoing debate regarding the GHG emissions from the production of biofuels, including the time profile of the emissions. The uncertainties and variability associated with the GHG reduction potential of biofuels are discussed in detail in NRC (2011). The values for GHG emissions used in this study were a modified version of those developed by EPA for the RFS2 final regulations. The difference was the treatment of emissions attributable to indirect land-use change (ILUC). The EPA analysis distributes the GHG emissions from ILUC over a 30-year period. For the analysis in this report, all emissions contributed by ILUC were attributed to the first year's operation of the biofuel conversion facility rather than spread over 30 years. This alternate ILUC treatment and its impact on annual biofuel GHG emissions are discussed in detail in Appendix G.5. These predicted GHG emissions do not include the use of CCS in the production facility to reduce overall well-to-wheels GHG emissions. Applying CCS to a biofuel production facility can potentially provide slightly negative well-to-wheels GHG emissions (NAS-NAE-NRC, 2009a).

3.3 ELECTRICITY AS A FUEL FOR LIGHT-DUTY VEHICLES

3.3.1 Current Status

In the United States, electricity is widely available, plentiful, and relatively inexpensive. It already is used as fuel for some LDVs available on the general market, including PHEVs (e.g., the Chevrolet Volt) and BEVs (e.g., the Nissan Leaf). Further, electric-power vehicles are in wide use in commercial applications such as in warehouses and factories.

3.3.2 Capabilities

Table 3.6 shows the 2010 capability of the U.S. electricity system (EIA, 2011a). The capacity factor measures the ability of a power source to produce power and reflects both availability to produce power and whether or not the plant is dispatched. Capacity factor is estimated as the annual electricity production for each source divided by the power production it would have achieved when operating at its net summer capacity 24 hours per day for the entire year. Power dispatch is affected by the price of the source relative to other competing sources because lower-priced sources are dispatched preferentially.

TABLE 3.6 Capability of the U.S. Electricity System in 2010

Source	Net Summer Capacity (GW)	Electricity Production (thousand GWh)	Capacity Factor
Coal	318.1	1,879.9	0.67
Oil and natural gas steam	113.5	123.9	0.13
Natural gas combined cycle	198.2	733.8	0.42
Diesel/conventional combustion turbine	138.6	51.0	0.11
Nuclear	101.1	802.9	0.90
Pumped storage	21.8	–0.2	–0.001
Renewables	123.0	371.6	0.35
Total	1,014.4	3,962.8	0.45

The average U.S. retail price for electricity is about $0.10/kWh with substantial variation across the country because of the time of use, local generation mix, and various incentives or taxes. In general, electricity produced by hydro power costs the least, followed closely by coal, nuclear, and natural gas. Electricity generation from natural gas is expanding rapidly for the following reasons:

- The cost of natural gas generation strongly depends on the cost of fuel. Currently the cost of natural gas is low ($2.5 to $3.5/million Btu) and could remain low for a decade or more.
- CO_2 emissions per unit of power generated by natural gas are about half of the CO_2 emissions per unit of power generated by coal.
- Emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x) and other toxic air pollutants from natural gas are much lower than the emissions from coal.

Gas turbines are well suited to provide backup power for intermittent renewable energy generation sources, such as wind and solar, because they can be ramped up relatively quickly. Because of this characteristic, the share of electricity generation from natural gas tends to increase as renewable energy increases. The generation of electricity produces GHG emissions, mainly CO_2. In 2010, total GHG emissions from electric power as reported in the AEO 2011 were 2.3 billion metric tons CO_2e (EIA, 2011a). There are additional emissions further upstream in the process, for example, in mining coal, producing natural gas, transporting fuels to the power plant, and building solar panels, wind turbines, and power plants. These upstream emissions can be added to the combustion emissions to estimate the total life-cycle emission of any process, including electricity generation. Life-cycle emissions are considered in this report's analyses of GHG emissions.

The capability (and demand) for electricity generation in the United States is expected to grow slowly from the present to 2050. For the purposes of this study, two cases in the

AEO 2011 (EIA, 2011a) were examined: the 2011 reference case and the GHG price case (hereafter referred to as the low-GHG case). The low-GHG case is based on a steadily escalating carbon tax beginning at \$25/metric ton of CO_2e in 2013 and escalating at 5 percent per year, reaching \$152/metric ton in 2050. The National Energy Modeling System (NEMS) is used by EIA to produce the AEO projections up to 2035. Therefore, the reference and low-GHG cases had to be extrapolated to 2050. For the low-GHG case, the total GHG emissions, power output, and cost data were extrapolated to 2050 using the years 2031 to 2035 to better capture the accelerating effects of the carbon tax increase in shifting the mix of generation sources. For the reference case, data from the period 2020 to 2035 were used because the mix of generation sources does not change much.

The low-GHG case shows that the annual GHG emissions in 2050 are reduced from the reference-case emissions by more than the desired 80 percent; however, this result does not account for the life-cycle emission effects in the electricity-generating sector because in the AEO analyses some of the emissions are attributed to other sectors. To compare fuels used in transportation on a consistent basis, the additional upstream generation of GHG emissions for combusted fuels will have to be included to account for the life-cycle emissions for non-combusted fuels, for example, renewables and nuclear.

For coal and natural gas, the upstream emission factors in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET model; Argonne National Laboratory) were used to calculate the total life-cycle emissions.

The AEO 2011 estimated GHG emissions from coal combustion to be 0.9552 kg CO_2e/kWh.[18] For coal, the upstream emissions embedded in the GREET model are 3.74 kg CO_2e/GJ. Using a conversion factor of 1.055 GJ per million Btu and assuming a heat rate of 10,000 Btu/kWh for the conversion of coal to electricity, the upstream emissions are 0.04 kg CO_2e/kWh. Accounting for transmission line losses of 7 percent, the correction from both upstream and transmission line losses is an additional 0.042 kg CO_2e/kWh, making the total emissions for coal-fired electricity 1.0 kg CO_2e/kWh.

The existing value for natural gas combustion emissions in the AEO model is 0.433 kg CO_2e/kWh.[19] The upstream GHG emissions for natural gas in the GREET model are 13.4 kg CO_2e/GJ. The heat rate used in AEO 2011 for converting natural gas to electricity is 8,160 Btu/kWh. Using this as a conversion factor, the upstream emissions of natural gas are 0.115 kg CO_2e/kWh. Correcting for transmission line losses of 7 percent makes the total correction 0.123 kg CO_2e/kWh, and the total GHG emissions for natural gas are 0.556 kg CO_2e/kWh.

There are no GHG emissions assumed in the AEO cases for nuclear and renewable electricity. The life-cycle emissions for nuclear and renewable energy sources were assumed to be 0.02 kg CO_2e/kWh, based on the values used in the NRC report *America's Energy Future. Technology and Transformation* (NAS-NAE-NRC, 2009a). Table 3.7 summarizes the results for GHG emissions from fuels.

In addition to extending beyond the AEO's 2035 projections, the current study had to verify that the low-GHG case still gives the desired result of about an 80 percent reduction in GHG emissions by 2050 after all emissions in the life cycle are accounted for. The fraction of electricity generated by each fuel was estimated by extrapolating the 2035 AEO results to 2050. Because the changes in the fuel mix were accelerating in the latter period of the EIA case, 2031-2035, the rate in that period was used as a reasonable basis from which to extrapolate. The result is shown in Table 3.8, which indicates that the GHG emissions are still reduced by more than 80 percent in 2050.

TABLE 3.7 2010 Electricity-Generation GHG Emissions by Source

Source	Combustion Emissions (kg CO_2e/kWh)	Upstream Emissions (kg CO_2e/kWh)	Life-Cycle Emissions (kg CO_2e/kWh)
Coal	0.9552	0.042	1.0
Natural gas	0.433	0.123	0.556
Nuclear	0	0.02	0.02
Hydro	0		
Renewables	0	0.02	0.02

SOURCE: EIA (2011a).

TABLE 3.8 Key Parameters of the AEO Base Case and Low-GHG Case

Parameter	2010	2020	2035	2050
AEO base-case cost (\$/kWh)	9.6	8.8	9.2	9.4
AEO low-GHG case cost (\$/kWh)	9.6	11.2	12.7	14.8
Carbon tax (\$/metric ton CO_2e)	0	35	73	152
AEO base-case output (billions kWh)	3,963	4,158	4,633	5,140
AEO low-GHG case output (billions kWh)	3,963	3,823	3,976	4,190
AEO base-case GHG emissions (kg CO_2e/kWh)	0.586	0.535	0.545	0.541
AEO low-case GHG emissions (kg CO_2e/kWh)	0.586	0.412	0.256	0.111

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[18] See http://205.254.135.24/oiaf/1605/coefficients.html.

[19] See http://205.254.135.24/oiaf/1605/coefficients.html.

3.3.3 Grid Impact of Plug-in Electric Vehicles

Neither of the AEO grid models account for the additional load if a large number of electric-powered vehicles are added. To assess the importance of this effect, the energy demand in 2020, 2035, and 2050 was estimated (Table 3.9).

The electricity generation projection in the low-GHG case is the comparison standard because the grid capacity is lower than that in the reference case. The result of this comparison shows that the additional load from PEVs in 2020 and 2035 is a small fraction of the projected total electricity usage and probably well within the uncertainty in the projections. Between 2035 and 2050, the power demand for PEVs is assumed to rise quickly. By 2050, it is assumed to reach 7 percent of the projected power usage and has a growth rate of about 0.5 percent per year. This load increase is well within the historic growth of the grid, which has been as high as 7 percent per year in the mid-1980s, and even the growth rate of 1 to 2 percent per year that has been true over the past 10 years in the United States. However, the low-GHG case projects load growth of less than 0.1 percent a year in the absence of BEV demand. Further, adding plants to the grid is a time-consuming process, and construction of a new plant can take a few years to a decade or more. Therefore, if the low-GHG case is an accurate projection of electricity usage, additional capacity has to be planned, permitted, funded, and constructed at a more rapid pace than projected for the next 20 years as large numbers of PEVs come into service (Table 3.10). If these additional plants cannot be brought online quickly enough, then the growth of PEV use may be restrained or the low GHG emissions may not be achieved as older plants with higher emissions may be required to be kept in service. New plant demand can be reduced to the degree that load shifting to off peak can be used. The amount of this reduction is not well defined.

There are also temporal and local effects on power demand from PEV charging. If owners charge their PEVs during times that the grid is highly used (e.g., during peak load periods), there could be problems with supplying enough electricity. For instance, if most PEVs are returned to their home base late in the afternoon with depleted batteries and are plugged in to charge, this load will be superimposed on the grid at a time when the daily load is already highest. This is especially true in the summer and winter seasons because of air conditioning and heating demands. It also may be desirable to move the load off peak to reduce GHG emissions because when peak loads are high, the oldest and likely dirtiest sources of power will be forced into service. They would not be used when power demands are well below the peak. Based on the estimates above, the peak loading issue until 2035 is unlikely to be a problem overall. But as the LDV charging load on the grid grows, the peak loading becomes of greater concern. However, studies have shown that practical, effective means are available to move the load to alternate charging times (e.g., late at night when other loads are low). One method that utilities are considering using to change consumer behavior is time-of-use (TOU) pricing, which would charge consumers lower rates during off-peak hours (generally between 11 p.m. and 5 a.m.). However, studies show that more comprehensive, integrated, and intrusive load management approaches based on the wide use of smart grid technology can be even more effective than incentives such as TOU pricing in reducing the peak load.

TABLE 3.9 Electric Vehicle Energy Demand Compared to Low-GHG Case

	2030	2035	2050
AEO low-GHG output (billion kWh)	3,823	3,976	4,190
Electric vehicle energy demand (billion kWh)	3.4	72	286
Electric vehicle energy demand (percent of output)	0.1	1.8	6.8

NOTE: The demand for electric vehicles was estimated assuming 13,000 miles as the base. The number of miles driven for each vehicle was taken from Elgowainy et al. (2009). The assumed number and mix of vehicles used to estimate the charging load are shown in Table 3.10. The number of vehicles, number of miles, and fraction of the fleet are not predictions by the committee, but were selected to be conservative (high) to illustrate the impact of the charging demand on the grid. For all vehicles the energy consumption is 0.286 kWh/mi.

TABLE 3.10 Assumed Number of Electric Vehicles in Fleet

	2020	2035	2050
Total electric vehicles	2 million	30 million	100 million
Fraction PHEV10	0.4	0.1	0
Fraction PHEV40	0.4	0.5	0.3
Fraction BEVs	0.2	0.4	0.7

NOTE: BEV, battery electric vehicle; PHEV, plug-in hybrid electric vehicle.

The present power grid has an estimated capability to handle a large fraction of the nationwide LDV fleet simply by taking advantage of the excess capacity in off-peak hours at night (PNNL, 2007). However, that estimate represents a nationwide average, and excess capacity varies throughout the country. For example, while Texas could provide energy for 73 percent of its LDV fleet, the California and Nevada area only could recharge 15 percent of its local fleet with off-peak power. This rate could be problematic given the large number of vehicles present in this region. With larger penetration of PEVs over the coming decade (about 25 percent), it has been suggested that there will be significant strain in regions such as California if the grid does not adapt (Guo et al., 2010).

The local distribution grids of each utility could also be affected by a significant deployment of PEVs (or even by a small number of PEVs if they are concentrated in a small area served by a small number of local transformers). The most likely upgrade required by the addition of PEVs is the replacement of transformers. A study by the Electric Power Research Institute and the Natural Resources Defense Council (EPRI and NRDC, 2007) and discussions by the committee with Pacific Gas and Electric Company (Takemasa, 2011) and previous discussions with Southern California Edison (Cromie and Graham, 2009) indicate that the local grid effects are manageable and within the utilities' normal cost of doing business. See Appendix G, Section G.2, for more discussion and an estimate of the investment cost.

3.3.4 Costs

There are four potential major sources of investment costs beyond the cost of the electricity itself:

- Charging stations to transfer energy from the electric distribution system to the PEVs;
- Necessary upgrades to the transmission and distribution system uniquely associated with charging PEVs;
- Additional generation capacity needed to provide fuel for large numbers of PEVs; and
- Conversion of the electric power system to realize approximately 80 percent lower annual GHG emissions.

These investment costs are estimated in Appendix G.6. The results are summarized in the following sections.

3.3.4.1 Charging Station Costs

Three types of charging stations are available. Level 1 charging stations use normal 110 V circuits and provide AC power to the vehicle. They are relatively low power and require typical charging times of over 20 hours for a 24 kWh battery. Level 2 charging stations provide AC power via a 240 V circuit (typically used today for electric clothes dryers and electric stoves). Because energy flow goes as the square of the voltage, level 2 charging stations will cut the charging time by a factor of about four. So for today's batteries, the charging time will decrease to a few hours. Level 3 charging stations convert AC line voltage and provide high-voltage DC to the vehicle. DC stations are not suitable for home use, and DC will likely be provided at charging stations analogous to gas stations. Level 3 charging stations now can charge a typical battery of an electric vehicle to 80 percent of capacity—the recommended maximum level to avoid damage and hence reduction in battery life—in 15 to 30 minutes. Preliminary data available to date suggests there will be very limited use of DC fast chargers and that the price of charging will be significantly higher than charging at home using a level 1 or level 2 charging station.

The bulk of the charging station investment cost will be borne by the electric-vehicle owner. Longer electric-only driving distances require larger batteries and more powerful charging stations, and so the investment cost is a function of the type of electric vehicle. Appendix G.6 estimates these costs per vehicle for a wide range of electric-vehicle types, assumes appropriate charging station mixes for both home and commercial installations, and includes the reference and low-GHG grid cases to 2050. Current costs for charging stations per vehicle range from about $800 for a PHEV10 to about $4,200 for a BEV. By 2050 the investment costs per vehicle will have dropped from about $450 for a PHEV10 to about $1,950 for a BEV. Appendix G.6 also converts these costs to $/gge per day for comparison with other fuels. These costs do not include a cost for a parking space for access to charging. The parking space for access to charging is a significant additional barrier as the EIA Residential Energy Consumption Survey (2009) reported that 52 percent of households cannot park a car within 20 feet of an electrical outlet.

3.3.4.2 Costs of Additions and Changes to the Transmission and Distribution System

The upgrade costs for high-voltage transmission are included in the next two sections. The investment costs for the distribution system are considered to be relatively small and manageable by the local utilities. They likely will be included in the price of the electricity. Therefore, no additional capital costs are included.

3.3.4.3 Cost of Additional Generation Needed for Large Numbers of PEVs

The additional energy demand from 100 million PEVs in 2050 is estimated to be about 286 billion kWh. Meeting that additional demand by new plants will require the addition of the equivalent of about 90 1,000-MWe plants at a cost of about $360 billion for new generating capacity and a total of over $400 billion, including the associated high-voltage transmission system additions.

3.3.4.4 Cost of Conversion of the Power System to 80 Percent Lower Annual GHG Emissions

Beyond the addition of new capacity to provide fuel for PEVs, a large additional investment would be required to reduce the annual GHG emissions from the entire U.S. power system by about 80 percent by 2050. This investment cost is estimated to be about $1 trillion. This cost is required to decarbonize the power sector and is not attributable solely to the LDV sector.

3.3.5 Regional and Local Effects

Regional and local effects for electricity-fueled LDVs influence the method of rolling out the charging infrastructure and changes in distribution system. They also affect the attractiveness of electricity as a fuel because of the pricing and GHG emissions of the local grid and because of dominant local use of vehicles versus electric-vehicle characteristics.

The rollout of a robust charging infrastructure is coupled to robust sales and use of PEVs, especially BEVs as opposed to PHEVs, because PHEVs can make use of liquid fuel if electricity charging is unavailable. Automobile manufacturers offering BEVs and PHEVs reported to the committee that they have found most sales to date occurring in urban areas with high income levels and a high proportion of people who are more environmentally minded (Diamond, 2010). Thus, the logical basis for expansion of the use of PEVs and the associated charging infrastructure is to proceed in urban areas in which vehicle and charging infrastructure builds rapidly and achieves the needed critical density. As time goes on, these centers are likely to expand and connect along major transportation corridors to provide power to the large number of BEVs needed to substantially reduce petroleum use and GHG emissions. Government support should follow this natural growth pattern and concentrate initial resources in limited areas rather than supporting a broad use of BEVs and expanded charging networks at many locations. Once the process is successful in one "center," the support there can be phased out and moved to another fertile area (Electrification Coalition, 2009).

Although the U.S. power grid is interconnected, the flow of electricity from all sources to all loads is not perfect. In effect, the country is divided up into a number of regional networks that, while strongly connected internally, have weaker ties to one another. As a result, there are significant regional and even state-to-state differences in pricing and GHG emissions. Electricity as a fuel costs less than gasoline, but customers in areas with higher electricity prices realize smaller fuel-cost savings. Some regional networks with relatively low electricity prices may emit significantly more GHG emissions than others with higher electricity prices (Anair and Mahmassani, 2012). GHG emissions may also be a function of available margin and peak loading on the local grid. Even if the base-load power generation has low GHG emissions, the older and dirtier power sources will be dispatched as the load rises. Thus, the GHG emission characteristics of the local grid might also affect the attractiveness of PEVs to buyers with strong environmental concerns.

The dominant use of the vehicle interacts with the characteristics of the PEVs, and this is likely to vary regionally. BEVs are used primarily as short-commute passenger vehicles and in fleets as vehicles for light hauling, or for relatively short-distance services. Those uses match the BEV's battery capability and charging time requirements and suggest that BEVs initially, and perhaps permanently, will be concentrated in urban locations. BEVs will not be in wide use in rural areas with longer drives and more widely separated charging locations.

3.3.6 Safety

The electrical safety considerations in providing electricity to the vehicle are generally well in hand. For both residential and business charging, the voltages and power levels are well within the state of practice, and safety provisions are well understood and codified. One of the costs associated with charging station installation is that it must meet the requirements of the national and local electrical codes, which means that it will most likely have to be installed by a licensed electrician and inspected and permitted by the appropriate governmental agency. For DC fast chargers used as public chargers, very high power connections between the charger and the vehicle must be made, and additional care is warranted. There are standards in use now for DC charging stations that fall under the formal jurisdiction and requirements of the national, state, and local electrical codes.

3.3.7 Barriers

There do not appear to be technical barriers in the electrical system upstream of the vehicle. There are, however, several potential financial and societal barriers:

- The investment cost for the charging infrastructure is borne largely by the vehicle owners.
- The capital cost for the full implementation of the needed changes to achieve a low-GHG-emitting electrical power system is large.
- Coordinating the needed investments and infrastructure work will require overcoming the complexity of the power system's unique ownership, management, and regulatory situation. The electric power system is regulated by a large number of local, state, regional, and federal entities. In most cases, the investors and owners of the transmission and distribution infrastructure are not the same as the investors and owners of the generating sources. Further, in some cases no benefits may accrue to some of those that have to make investments, such as states that have neither the loads nor the generation sources, but must support transmission lines between adjacent states that have loads and sources.
- Permitting and construction of new power system assets are very time consuming. Large power plant projects and large transmission and distribution system projects can take several years to over a decade to complete.

Finding: For electricity as a fuel for LDVs to be effective in reducing net GHG emissions, the entire U.S. electric power system has to shift largely to electricity production from sources that emit low GHG emissions (for example, nuclear, renewables, and natural gas with or without CCS).

3.4 HYDROGEN AS A FUEL

3.4.1 The Attraction of Hydrogen

When hydrogen is used as a fuel in fuel cell electric vehicles (FCEVs), the only vehicle emission is water. When hydrogen is used in an internal combustion engine, the emissions are water, some nitrogen oxides, and some trace chemicals mostly as a result of using lubricants. Although CO_2 emissions are absent from vehicle emissions when hydrogen is used as an LDV fuel, varying amounts of GHGs are emitted during hydrogen production. The amount depends on the primary fuel source and the technology used for hydrogen production. Most of the hydrogen on Earth is found in either water or hydrocarbons such as coal, oil, natural gas, and biomass. Because of the diverse primary sources for hydrogen, an amount of hydrogen large enough to fuel the entire LDV fleet could be made with only domestic sources. Different process technologies can be used with different primary sources to make a pathway for delivering hydrogen to consumers at different costs and with varying amounts of GHG emissions. The diversity of supply sources and production technologies is an advantage of hydrogen fuel.

3.4.2 Major Challenges

For more than 10 years, there have been serious efforts in the United States, Europe, and Japan to develop FCEVs and the needed production and delivery technologies to supply hydrogen. As Chapter 2 indicates, there has been considerable success in developing FCEVs, but some challenges remain. There also has been considerable success in developing production, distribution, and dispensing technologies for making and delivering low-cost hydrogen, but major challenges still exist. The two major challenge areas are the following:

- Making low-cost hydrogen with low GHG emissions. At present, the lowest-cost methods for hydrogen production used by industry are based on fossil fuels and have associated GHG emissions of varying amounts. The low-GHG methods are currently more expensive and need further development to become competitive.
- Building the hydrogen infrastructure will be a large, complex, and expensive undertaking. Hydrogen-fueling stations would have to be available before FCEVs can be sold. Until a large number of FCEVs are in use, the cost of hydrogen as a fuel will be high. Because FCEVs are new and hydrogen as a consumer fuel is new, there are many practical concerns such as safety, codes and standards, permitting, and zoning issues that need to be addressed before growth can flourish.

3.4.3 Current Status of the Market

Hydrogen as an industrial commodity is produced in large quantities in the United States and in many other countries. The amount of hydrogen produced is over 50 million tons per year worldwide (Raman, 2004; IEA, 2007) and over 10 million tons per year in the United States (EIA, 2008b). Most of the hydrogen is used in the chemical processing industry and in refining crude oil, and most of it is produced in large facilities closely associated with the end use. Over 95 percent of U.S. hydrogen is made from natural gas, with other sources including refinery off-gases, coal, and water electrolysis. Several hydrogen pipeline systems (Houston, Los Angeles, and Chicago) exist to move large quantities of gaseous hydrogen between nearby industrial users with over 1,200 miles of hydrogen pipelines. Some established industrial gas companies produce, store, and distribute hydrogen as either a gas or a cryogenic liquid to smaller users by truck. The demand for hydrogen for industrial use has increased consistently for several decades.

Even as the infrastructure for producing, delivering, and using large amounts of hydrogen for this industrial market is well developed, the infrastructure for producing, delivering, and dispensing hydrogen for use as a transportation fuel has yet to be developed. For illustrative purposes, if hydrogen were to be used as a transportation fuel, then the current U.S. production level of 10 million tons per year would be enough to fuel about 45 million cars (at 60 mpgge and 12,000 mi/yr). There is, however, little spare capacity in the existing system for this new market. Therefore, a new hydrogen infrastructure is needed before large numbers of FCEVs are produced. This infrastructure will need to be much different from the existing one because it has to focus on wide distribution of small amounts if distributed through retail outlets, similar to what is done for gasoline today.

Academic, industrial, and government efforts over the past 10 years to define this retail-fuel-oriented infrastructure have mapped out the needed technology improvements, established performance criteria for different parts of the infrastructure, estimated the cost of hydrogen and the infrastructure over time, and suggested possible implementation methods. The NRC report *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen* (NRC, 2008) contains an analysis of the technical needs, costs, petroleum savings and GHG emission savings possible by moving towards a hydrogen-fuel infrastructure.

3.4.4 Hydrogen Infrastructure Definition

Rather than being built throughout the entire United States before FCEVs are available, a hydrogen infrastructure likely will first be started in a few markets. Then the infrastructure will be built up in conjunction with increasing local FCEV sales. The concentration of demand will result in a decrease in the high initial cost of hydrogen and the infrastructure as equipment for commercial-scale production is installed and used at commercial rates. This process will then be repeated in additional markets until a critical mass of FCEVs and hydrogen stations is built to a market-sustainable level.

The first hydrogen stations are likely to be supplied by truck delivery from local hydrogen-distribution points. This is a high-cost method that may be largely replaced by hydrogen stations with on-site hydrogen generation capabilities where the hydrogen is made at the retail station rather than supplied from the large plants that now supply the bulk of hydrogen. This approach precludes the need to transport or deliver hydrogen, and the distributed hydrogen generation equipment can be sized for the demand. Several technologies are available for the small hydrogen generators, including natural-gas reforming, water electrolysis, and biofuel reforming.

- *Small natural-gas reforming*—The process is the same as that used in today's large natural-gas reforming facilities. However, the reforming apparatus for fuel is small and packaged such that it looks like a large appliance. These reformers have been demonstrated at a number of hydrogen-fueling stations in the United States, Europe, and Japan. CO_2 produced in the process is released to the atmosphere because capturing it is difficult.
- *Small water electrolysis*—Commercial alkaline water electrolysis units are available and have been demonstrated in small hydrogen stations. GHG releases are associated with the source of electricity and can be high or low depending on how the electricity is produced.
- *Small biofuel reforming*—Ethanol reforming and other biofuel reforming have been demonstrated in laboratories, but research and development (R&D) is still needed to increase hydrogen yields and lower costs to be competitive with small natural-gas reformers and small water-electrolysis methods. GHG releases can be low depending on the source of the biofuel.

As the demand for hydrogen increases in a local market, there will come a point when large centralized facilities similar to today's will produce hydrogen at lower cost than is possible with small distributed generators. These facilities will also offer the opportunity to make low-GHG hydrogen through the use of other primary fuels and CCS technology. Several primary feedstock and technology choices are possible, including natural-gas reforming, coal gasification, biomass gasification, and large-scale wind or solar electrolysis.

- *Natural-gas reforming*—This low-cost process is widely used now for generating large amounts of hydrogen. CCS is possible but has not yet been demonstrated with a hydrogen plant.
- *Coal gasification*—This process has been used commercially for decades, but high CO_2 releases require that CCS be available. CCS has not been demonstrated with coal gasification.
- *Biomass gasification*—This process has been demonstrated in the laboratory, but not yet at large pilot-scale facilities. Further development is needed. If CCS is used, then biomass gasification becomes a CO_2 sink with negative releases.
- *Large centralized electrolysis with wind or solar power*—The process is still being researched to lower costs. This process has low GHG emissions.

Other hydrogen-production methods under research hold long-term promise for making hydrogen at low costs, low GHG emissions, or both, but they are not yet developed enough to understand the availability or the cost implications. Some of these methods include nuclear high-temperature chemical cycles or electrolysis, photoelectrochemical methods, and biological systems.

3.4.5 Hydrogen Dispensing Costs and GHGs

The cost of making, transporting, storing, and dispensing hydrogen at a station has been estimated for all of the primary feedstocks. These estimated costs are highly dependent on many assumptions and can vary considerably depending on future technical advances, feedstock costs, and how quickly the market develops (scale). The estimated costs for some of the different hydrogen pathways based on future technology development are shown in Table 3.11. The estimates are expressed in dollars per gallon of gasoline equivalent ($/gge). A gge of hydrogen contains as much energy (Btu) as a typical gallon of gasoline and is defined as 116,000 Btu/gge in this study. The future price basis and resource requirements used to generate the costs in Table 3.11 are shown in Table 3.12. The hydrogen costs in Table 3.11 are in some cases up to $1.00/gge higher than those determined in prior studies

TABLE 3.11 Hydrogen Costs at the Pump ($/gge), Untaxed

	2010	2020	2035	2050
Distributed natural gas reforming	3.50	3.60	3.90	4.20
Distributed grid electrolysis	5.80	5.40	5.50	5.69
Coal gasification without CCS	3.80	3.80	3.80	3.85
Coal gasification with CCS	4.50	4.50	4.50	4.50
Central natural gas reforming without CCS	3.30	3.40	3.70	4.10
Central natural gas reforming with CCS	3.60	3.60	4.00	4.30
Biomass gasification without CCS	4.10	4.10	4.10	4.10

NOTE: Basis: 2008 H_2A future cases updated to 2009 dollars using CEPCI and Nelson-Ferrer cost indexes and the AEO 2011 price basis. $2.00/gge included for distribution and station costs for central methods and $1.88/gge included for station costs of distributed methods.

TABLE 3.12 Resource Prices and Requirements Used in Table 3.11

	2010	2020	2035	2050
Industrial natural gas, \$/million Btu	4.80	5.36	7.21	9.06
Delivered coal, \$/ton	45.9	46.1	48.9	50.2
Industrial electricity, \$/kWh	0.068	0.061	0.064	0.067
Delivered biomass, \$/ton	75.0	75.0	75.0	75.0
Coal needed, kg/gge H_2	9.8	9.8	9.8	9.8
Biomass needed, kg/gge H_2	12.8	12.8	12.8	12.8
Natural gas needed, cubic ft/gge H_2	170	170	170	170
Electricity needed, kWh/gge H_2	45	45	45	45

NOTE: Basis—AEO2011 (EIA, 2011a) resource prices and 2008 H_2A future cases for resource requirements

(NRC, 2008, for example). The increased costs compared to the earlier NRC study result from several factors:

- The costs in the current study are based on the 2008 version of the hydrogen analysis (H_2A) production model developed by DOE, whereas the ones in the previous study (NRC, 2008) were from the 2005 version.
- The distribution costs are estimated to be \$2/gge, whereas prior ones were \$1.00 to \$2.00/gge.
- The capital costs are inflated based on actual construction cost inflation to 2009 dollars.
- The costs for biomass and coal are nearly twice what they were in the 2008 study.

The costs in Table 3.11 represent future costs based on using commercial-scale processes and are possible only after about 10 million FCEVs are on the road. Prior to this, the hydrogen cost will be higher because of underutilized or smaller-scale production facilities. Figure 3.3 shows hydrogen costs versus number of FCEVs.

The GHG emissions associated with producing, delivering, and dispensing hydrogen at a station on a life-cycle basis are shown in Table 3.13. This includes an upstream component related to the emissions associated with production and delivery of the base fuel to the hydrogen production plant and, if used, the energy needed to sequester CO_2 plus a component for conversion, delivery, and dispensing of GHGs.

3.4.6 Hydrogen Infrastructure Needs and Cost

Building the infrastructure for delivering hydrogen over the vast size of the United States is a significant challenge for the use of hydrogen for transportation. It requires developing some new technologies, establishing codes and standards, overcoming the problem of interdependence of establishing a critical mass of hydrogen-refueling stations and FCEV sales, overcoming the high initial cost of hydrogen, and increasing the use of production methods with low GHG emissions.

The total investment costs used to calculate the hydrogen costs in Table 3.11 for future technologies used at commercial-size plants are shown in Table 3.14. These

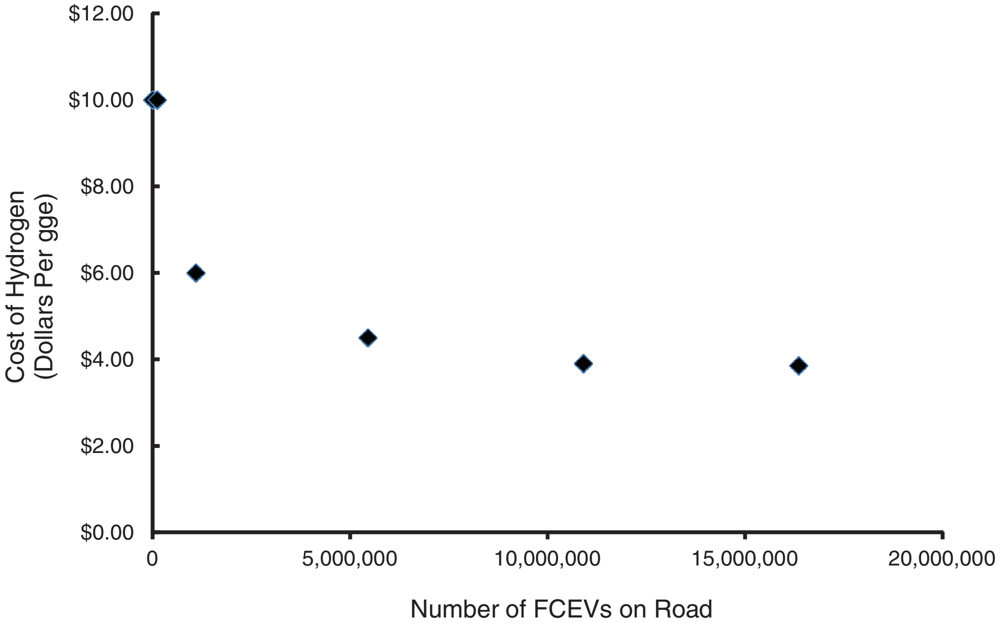

FIGURE 3.3 Hydrogen cost versus number of FCEVs.

TABLE 3.13 Total GHG Emissions (kg CO_2e per gge of hydrogen)

H_2 Production Method	Upstream CO_2e	Plant, Delivery and Dispensing CO_2e	Total CO_2e
Distributed natural gas reforming	2.78	8.66	11.44
Distributed electrolysis, current grid	35.44	0	35.44
Coal gasification without CCS	1.13	24.67	25.81
Coal gasification with CCS	2.77	2.47	5.24
Central natural gas reforming without CCS	2.18	9.28	11.46
Central natural gas reforming with CCS	2.71	0.93	3.64
Biomass gasification without CCS	–24.37	24.57	0.20

NOTE: Basis—H_2A 2008 future cases modified to use GREET 2011 upstream natural gas figures.

costs are normalized to 2009 dollars per gallon of gasoline equivalent per day of produced hydrogen. The station costs appear to be the largest factor for all but coal technology. The station costs include all costs associated with building grassroots new stations that include hydrogen storage, compression, and dispensing and are the same for each technology. The actual hydrogen production investment costs are shown separately. Investment costs for CCS are included for the large coal and natural gas facilities.

The NRC report *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen* (NRC, 2008) outlined one possible hydrogen infrastructure development pathway out to 2050 and estimated the hydrogen cost, GHG emissions, and investment needs over different time periods. The pathway in that report starts with distributed natural gas reforming. As demand increases, coal gasification with CCS and biomass gasification provide the bulk of increased hydrogen production. This is not the only possible pathway to supply the increasing amount of hydrogen, but it relies on some current, low-cost, and mostly commercially developed processes. With future R&D success, other technologies would likely become part of the transition.

TABLE 3.14 Investment Costs ($/gge per day)

H_2 Production Method	Plant + CCS	Distribution	Stations	Total
Distributed natural gas reforming	700	0	2,345	3,045
Distributed electrolysis, current grid	860	0	2,345	3,205
Coal gasification without CCS	2,250	225	2,345	4,820
Coal gasification with CCS	3,020	225	2,345	5,590
Central natural gas reforming without CCS	400	225	2,345	2,970
Central natural gas reforming with CCS	740	225	2,345	3,310
Biomass gasification without CCS	1,040	225	2,345	3,610

With the increasing amounts of domestically available natural gas and the lower prices for natural gas compared to crude oil projected in the AEO 2011 (EIA, 2011a) study price basis, several other combinations of basic resources and hydrogen-production processes could be viewed as possible in the future with different hydrogen costs and GHG emissions. Some of the many possible pathways for making large amounts of hydrogen are shown in Table 3.15 with the resulting long-term hydrogen cost and GHG emissions.

- *A low-cost case*—The emphasis is on low-cost hydrogen from several resources with little to no emphasis on GHG reductions. Hydrogen is produced from: 25 percent distributed natural-gas reforming, 25 percent coal gasification without CCS, 25 percent central natural-gas reforming without CCS, and 25 percent biomass gasification without CCS.
- *A partial CCS case*—The emphasis is on low-cost hydrogen, but CCS is used for all coal and central natural gas processes. Hydrogen is produced from: 25 percent distributed natural gas reforming, 25 percent coal gasification with CCS, 25 percent central natural gas reforming with CCS, and 25 percent biomass gasification without CCS.
- *A low-GHG case*—The emphasis is on low GHG emissions with less regard to hydrogen cost. Hydrogen is produced from: 10 percent distributed natural-gas reforming, 40 percent central natural gas reforming with CCS, 30 percent biomass gasification without CCS, and 20 percent low GHG grid electricity for electrolysis.

3.4.7 Recent History

More than 200 FCEVs have been demonstrated in the United States over the past 10 years. Several of the auto companies developing FCEVs have gone through multiple iterations to improve performance. Five of these companies—General Motors, Daimler, Toyota, Honda, and Hyundai—have reaffirmed near-term (2015) commercializa-

TABLE 3.15 Alternate Scenario Hydrogen Costs and GHG Emissions

	\$/gge H_2	kg CO_2e/gge H_2
Low-cost case	3.85	12.2
Partial CCS case	4.10	5.1
Low-GHG case	4.80	2.6

tion plans for FCEVs. Because these are all multinational companies, the commercialization plans certainly will vary in different markets.

In the United States, there have been about 60 hydrogen fueling stations constructed to service the FCEV demonstration efforts (DOE-EERE, 2012a). Given that the number of vehicles is small, none of these stations is of even small commercial size. They demonstrate, however, the importance of distributed technologies to starting the infrastructure. General Motors has joined 10 companies, government agencies, and universities to build 20 to 25 hydrogen-fueling stations in Hawaii by 2015 (DeMorro, 2010). Several countries have formed much larger infrastructure plans and consortiums than the one in the United States to support early FCEV commercialization. In 2010 Japan announced plans for 1000 hydrogen stations and 2 million FCEVs by 2025 (DOE-EERE, 2011a). To support these goals, a consortium of 13 companies was established to focus on the hydrogen infrastructure. Germany has announced plans to build 150 hydrogen stations by 2013 and up to 1000 by 2017.

3.4.8 Barriers

Although technology is available to provide competitively priced hydrogen from natural gas, technology improvements are needed to provide low-cost hydrogen that is also low in net GHG emissions. Continuous government support for RD&D is required.

The robust performance and the durability of a fueling station with sustained high-volume usage remain to be verified through demonstration.

The high cost of the FCEV is a barrier to wide commercialization for the vehicles and hydrogen. A viable pathway is needed for creating the initial hydrogen infrastructure and for dealing with high initial hydrogen costs. This pathway likely will require government actions.

The lack of an incentive to provide low-GHG fuels in general reduces the benefits for transitioning toward alternative fuels. It also reduces the incentive to make hydrogen from the more costly but lower-GHG methods.

Perceived, real and unknown safety issues with hydrogen production and use especially in a consumer environment could result in delays in acquiring, zoning, and permitting authorizations. There are significant practical challenges of developing sites especially for urban stations within the footprint of existing fueling sites.

Finding: Making hydrogen from fossil fuels, especially natural gas, is a low-cost option to meet future demand from FCEVs; however, these methods result in significant GHG emissions. Making hydrogen with low GHG emissions is more costly (renewable electricity electrolysis) or requires new production methods (e.g., photoelectrochemical, nuclear cycles, biomass gasification, and biological methods) and CCS to manage emissions. Continued R&D is needed on low-GHG hydrogen production methods and CCS to demonstrate that large amounts of low-cost and low-GHG hydrogen can be produced.

3.5 NATURAL GAS AS AN AUTOMOBILE FUEL

Natural gas can be used for transportation via several pathways, each of which has advantages and challenges (see Appendix G.7). None of them is of much commercial significance in the United States as of 2012.

Less than 3 percent of the natural gas consumed in the United States is for transportation, and most of that is used for powering the transportation pipeline and distribution system for natural gas. Natural gas as an automobile fuel will have to compete with other existing uses of the gas (for electricity generation, and for residential, commercial, and industrial uses). This section addresses the direct use of CNG in internal combustion engines (CNG vehicles, or CNGVs). The other pathways are considered in other sections of this report. Methanol as a transportation fuel is discussed in Appendix G.8.

3.5.1 Current Status

3.5.1.1 Net GHG Emissions from CNG Use

Natural gas from production wells is composed mostly of methane (70 to 90 percent), with some ethane, propane, and butane (0 to 20 percent), CO_2 (0 to 8 percent), N_2 (0 to 5 percent), H_2S (0 to 5 percent), traces of O_2, and traces of the noble gases Ar, He, Ne, and Xe (NaturalGas.org, 2011). Natural gas holds promise for providing part of the energy requirements of automobile transportation. Displacing a significant portion of petroleum-based fuels would have large societal and economic benefits by reducing the externalities associated with petroleum importation (e.g., supply and price instabilities, security and defense costs, oil import-related trade and export-import imbalances).

Natural gas vehicles, fueled by CNG or liquid natural gas, are among the most immediately attainable alternative-fueled vehicles. Given methane's molecular structure, natural gas has the highest energy content or hydrogen-to-carbon weight ratio of all fossil fuels. Nevertheless, the use of natural gas, like other forms of primary energy, has associated GHG emissions, including methane emissions, during exploration, well drilling, and the well-to-tank transmission for natural gas. Life-cycle analyses that account for upstream and downstream GHG emissions for natural gas have been published by the DOE's National Energy Technology Laboratory (DiPietro, 2010). In terms of kg CO_2e/million Btu, drilling and extraction generate 19.9 and pipeline transport generates 3.3 (mostly natural gas to power the pumps), for a total upstream (well to tank; WTT) of 23.2. Compression of natural gas into CNG from pipeline pressure to about 3,600 psi adds another 3.5 percent (range 2 to 5 percent), or 0.8 kg CO_2e/million Btu to the GHG emissions.

The Argonne National Laboratory's GREET model uses smaller WTT estimates. For example, the 1.8b version of that model released in September 2008 estimated the upstream emissions to be 9.6 kg CO_2/million Btu (ANL, 2011). The model estimated vehicle tank-to-wheel (TTW) CO_2 emissions of 53.9 kg CO_2/million Btu. Thus, the well-to-wheels CO_2 emissions for CNG as a fuel are 9.6 + 53.9 = 63.5 kg CO_2/million Btu. In 2011 the GREET model estimates were updated to include higher effects of methane leakage and other changes, yielding an upstream estimate of 14.2 kg CO_2/million Btu for shale gas. This estimate is used in this report for all pathways using natural gas as a primary source.[20] Another life-cycle analysis by Burnham et al. (2012) indicated that the life-cycle GHG emissions of natural gas are 23 percent lower than those of petroleum-based gasoline and 43 percent lower than those of coal. Jiang et al. (2011) estimated the life-cycle GHG emissions for producing electricity from shale natural gas to be 20 to 50 percent lower than the life-cycle GHG emissions for producing electricity from coal.

Fugitive natural gas emissions from increasing use of natural gas are the subject of current analyses. In 2010, the EPA reissued its methane emissions guidelines during natural gas extraction, with substantially increased figures versus their previous estimates (EPA, 2010a). Howarth et al. (2011) estimated the leak rate of methane as a percentage of total natural gas produced to be in the range of 3.6 to 7.9 percent. Of the methane leaked, 1.6 percent was attributed to methane escaping from flow-back fluids (1.6 percent) and from drill-out (0.33 percent). The remainder was attributed to venting and equipment leaks, and emissions during liquid unloading, gas processing, and transport, storage, and distribution. The methodologies and data used in the estimates of methane leakage by the EPA and by Howarth et al. were strongly critiqued by an IHS CERA report, *Mismeasuring Methane: Estimating Greenhouse Gas Emissions from Upstream Natural Gas Development* (Barcella et al., 2011). Analysis in that report suggests much lower fugitive methane emissions. Burnham et al. (2012) estimated methane leakage in the range of 0.97 to 5.47 percent for conventional natural gas pathways and 0.71 to 5.23 percent for shale-gas pathways. Methane leakage from the sources mentioned is a concern because of the large global warming potential of methane, but its extent is uncertain (Alvarez et al., 2012). The sources of leakage are amenable to various forms of reduction or control by conventional technologies, representing ongoing considerations in sorting out the environmental aspects of shale gas and conventional natural gas. Several studies are underway to consolidate and define fugitive natural gas emissions from shale-gas operations as of the writing of this report.

Recognizing that some cost-effective measures exist for reducing methane emitted from producing natural gas, in 2011, the EPA proposed amendments to its air regulations for the oil and gas industry that will reduce GHG and other emissions from exploration, drilling, and production (EPA, 2011c). The final regulation was issued in April 2012. In it, the EPA estimates reductions of 1.0 to 1.7 million tons per year of methane emissions associated with drilling and transportation of natural gas (EPA, 2012b).

3.5.2 Capabilities

3.5.2.1 Natural Gas Supply, Demand, and Prices

The United States used about 98 quads (quadrillion, or 10^{15}, Btu) of energy from the nation's primary energy sources in 2010 (LLNL, 2012). Of the 24 quads of natural gas consumed in the United States in 2010, 98 percent originated from North America and 85 percent was of domestic origin. (In comparison, the United States consumed 37 quads of petroleum, about 50 percent of which was imported.) Transportation used 28 quads of primary energy, 95 percent of which was from petroleum. With a typical 25 percent overall efficiency, a useful energy of about 7 quads is turning the wheels of the U.S. transportation fleet.

Of the 24 quads of natural gas, about 7 quads were used to generate electricity. Natural gas is becoming more attractive for electricity generation than coal, according to recent references quoting numbers from the DOE's Energy Information Administration (Begos, 2012). Electricity generation from natural gas in the United States increased from about 601 billion kWh in 2000 to 981 billion kWh in 2010. During the same period, electricity generation from coal declined from 1,966 billion kWh to 1,850 kWh (EIA, 2011b). Between 2010 and 2035, 80 percent of all newly added electricity generation capacity is expected to come from natural gas-fired plants (EIA, 2011a; NaturalGas.org, 2012). With recently increased concerns about the future of nuclear energy, some of the contemplated future nuclear electric capacity will likely shift to natural gas-fired power plants as well.

According to the June 18, 2009, report of the Potential Gas Committee on the assessment of the year-end 2008 natural gas reserves (Potential Gas Committee, 2009), the United States has 1,836 tcf (trillion, or 10^{12}, standard cubic feet; 1 tcf is equal to approximately 1 quad) of probable natural gas resources, defined as being potentially economically extractable by the use of available technology at the then-current economic conditions. The above number (1,836 tcf) is the sum of 1,673 tcf in traditional reserves and 163 tcf in coal-bed reservoirs. Of the 1,836 tcf of probable reserves, shale gas accounts for 616 tcf (33 percent). In addition to the above probable reserves, the United States also has 238 tcf of proved natural gas resources, defined as deemed to

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[20] The CNG GHG emissions are estimated as follows: 14.2 kg CO_2/million Btu upstream plus 59.8 kg CO_2/million Btu combustion plus 7 percent of this total for pipelining and compression = 79.2 kg CO_2/million Btu or 9.2 kg CO_2/gge.

be economically extractable (rather than being potentially extractable) or already being extracted economically. The estimated total natural gas reserves of 2,074 tcf (1,836 + 238) represent an increase of 542 tcf (35 percent) over the estimate in the previous biannual assessment. The natural gas consumption of the United States was about 24.1 tcf in 2010 (EIA, 2011b). Dividing the 2008 estimated total of probable and proved natural gas reserves by the 2010 annual consumption gives an estimate of 86 years' worth of natural gas. It has been argued that only a fraction of probable reserves can be recovered economically (Brooks, 2010), so that the "probable technically recoverable resources" would be only 441 tcf, of which 147 tcf is the shale-gas component.

The 2009 report upgraded the probable reserves mainly by reclassifying known shale gas reserves from possible to probable, due to the rapid evolution and deployment of new technology. The new shale gas extraction technology combines two technologies from the oil fields, horizontal drilling and hydraulic fracturing. (See Technology Review, 2009, for a video schematic of these processes.)

The newly reclassified shale gas reserves are located in Louisiana, Texas, the Rocky Mountains, West Virginia, Pennsylvania, and New York. There are large shale gas fields outside the United States as well, and these fields also are likely to be accessible via the new technology. The *BP Energy Outlook 2030* (BP, 2011) stated that in 2009, the world had 6,621 tcf of proved gas reserves, which would be sufficient for 63 years of production at 2010 production levels. Global reserves of unconventional natural gas could potentially add another 30 years to natural gas use.

Most of the natural gas-based transportation fuels are expected to gain new impetus in light of the dramatically upgraded estimates of global natural gas resources. Future natural gas supply and consumption volumes and prices, broken down to sources and uses, are published yearly by the U.S. Department of Energy's Energy Information Administration, AEO. The AEO 2011 early release projects to the year 2035 (EIA, 2012a). According to AEO (EIA, 2011a), between the years 2010 and 2035, natural gas consumption will grow by 16.8 percent. The share of shale gas will increase from 23 to 49 percent (Figure 3.4). The share of natural gas in transportation will remain at 3 percent, which roughly accounts for the amount of natural gas used for operating the pipelines. In other words, the 2011 AEO is not counting on any significant increase in the use of natural gas for transportation in the United States. This seems to also hold on the global scale. The *BP Energy Outlook 2030* (BP, 2011) projected global use of CNG for transport to be limited to 2 percent of the global demand for transportation fuels.

3.5.2.2 Will There be Enough Natural Gas for LDVs?

In the year 2000, the 110,000 natural gas vehicles in the United States consumed between 8.3 and 12.3 billion standard cubic feet of natural gas, which is between 0.036 and 0.053 percent of the U.S. natural gas consumption (Campbell-Parnell, 2011). According to the 2011 AEO (EIA, 2011a), the U.S. LDV vehicle stock will increase from about 128 million vehicles in 2011 to about 186 million vehicles in 2035. Assuming a 10 percent penetration of CNGVs in 2035 (EIA, 2011a), 45 mpgge, and 14,000 mi/yr, this would translate to a natural gas consumption of 0.73 tcf/yr. Natural gas consumption is forecasted by the AEO 2011 to increase from 24.1 tcf in 2010 to 26.5 tcf in 2035 (with only 6 percent for transportation; mostly natural gas consumed by powering the pipeline system itself). Therefore, a 10 percent CNGV penetration in the 2035 LDV fleet would add only 2.8 percent to the natural gas consumption in that year. Thus, the

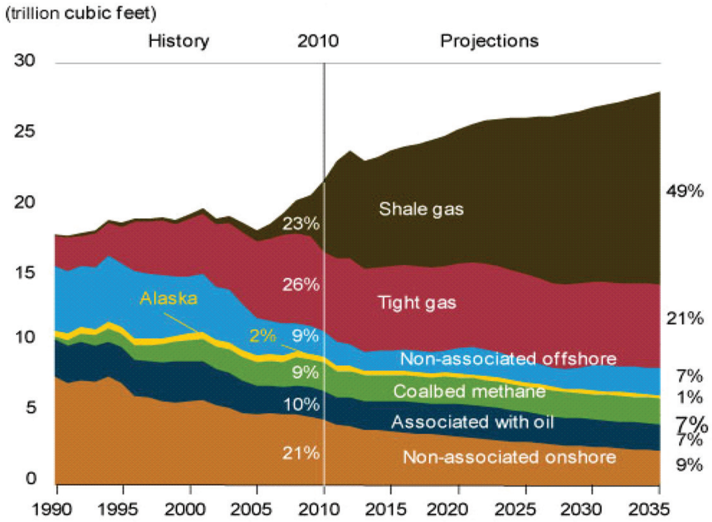

FIGURE 3.4 U.S. natural gas production (trillion standard cubic feet) from 1990 to 2035.
SOURCE: EIA (2012a).

natural gas supply is unlikely to limit the early penetration of CNGVs.

Several studies project that LDVs powered by natural gas will remain a niche for a while in the United States. Those studies include *The Future of Natural Gas* by the Massachusetts Institute of Technology (MIT, 2011), a market analysis of natural gas vehicles by TIAX (Law et al., 2010), an analysis of long-term natural gas demand by Simmons & Company (2011), and an analysis of natural gas demand for transportation by IHS-CERA (IHS, 2010). TIAX (Law et al., 2010) compared the incremental lifetime costs of LDVs using different technologies and found that the direct costs of natural gas vehicles are favorable compared to BEVs, PHEVs, FCEVs, and flex-fuel vehicles. They concluded that CNGVs could become significant with appropriate policy and incentive programs and projected the use of 5.5 billion gge of CNG (still only 0.7 tcf) by 2035.

The reasons for the slow and late development of light-duty CNGVs in the United States transcend the barriers of CNGV and vehicle conversion costs, lack of luggage and tank volume, and the lack of refueling infrastructure. Development of CNGVs also may be significantly hampered by the attractiveness of alternate uses of natural gas, specifically for electricity generation. The AEO 2011 (EIA, 2011a), for example, shows year 2016 levelized costs for electricity generated by 16 different power plant and fuel technologies. Of these, the lowest levelized cost is shown for natural gas-fired combined-cycle power plants (<7 cents/kwh), followed by hydro (8.64), conventional coal (9.48), wind (9.70), biomass (11.25), advanced nuclear (11.39), advanced coal with CCS (carbon capture and storage) (13.62), and photovoltaic solar (21.02). The AEO projections suggest that natural gas will indeed be most attractive for electric power generation because of its low levelized cost.

3.5.3 Costs

3.5.3.1 Natural Gas Fuel Costs and Cost Projections

At filling stations CNG and liquid natural gas are metered and sold on a gallon of gasoline-equivalent basis; the conversion factor of 1 gge = 5.66 lb of natural gas was determined by the National Institute of Standards and Technology (NIST). The prices of natural gas on a gallon of gasoline-equivalent basis are published on the Internet, and they vary by state, region, city, and individual filling station. Natural gas at the time of this writing had a price advantage of about \$1 to \$2/gge, depending on the particular filling station. For example, overall average U.S. fuel prices reported for the last quarter of 2011 were \$3.37/gal for gasoline, and \$ 2.13/gge natural gas (DOE-EERE, 2012b).[21]

At a price differential of \$1.24/gge in favor of CNG, 30 mpg, 13,000 mi/yr, and 433 gge/yr consumed, the fuel cost savings would be about \$540/yr, returning the original investment in a 2012 Honda Civic Natural Gas (versus the LX) in about 13 years (7,500/540 = 14 years). This payback period is not likely to be perceived by the consumer as economically attractive. Various states and the federal government have offered subsidies, which could amount to \$4,000 per vehicle. With a \$4,000 subsidy, the economic return period would be reduced to 6 years. CNG economics can thus be significantly better in the states that subsidize CNGVs.

Natural gas prices have declined in recent years, whereas oil prices have been rising. With fuel and vehicle subsidies for natural gas, any continued gasoline price increases could eventually make the original equipment manufacturers' natural gas vehicles economically attractive.

The appeal of natural gas as an automotive fuel depends to a large extent on the ratio of oil prices to natural gas prices (Figure 3.5). Long-term future natural gas prices have been forecasted by the 2011 AEO (EIA, 2011a) (Table 3.16).

The price customers would pay at the CNG filling station for filling a vehicle was calculated by taking the average of commercial and industrial prices for natural gas and adding a margin sufficient to generate a 15 percent return on an investment of \$1.3 million in a CNG filling station servicing 1,000 cars per week at 10 gge per fill per week. This margin was calculated to be \$7.76/million Btu or \$0.90/gge NG. (The operating costs and capital expenses of this filing station, excluding fuel costs, were \$273,351/yr.) CNG filing station costs and additional natural gas pipeline needs are discussed in Appendix G.9.

The U.S. Department of Energy's Alternative Fuels and Advanced Vehicles Data Center lists 975 public CNG refueling stations as of January 9, 2012 (DOE-EERE, 2012a). Unevenly distributed across the country, they are clustered primarily in California (229 stations), New York (106 stations), Utah (81 stations), Oklahoma (67 stations), Texas (35 stations), and Arizona (30 stations).

The distribution of CNG filling stations corresponds somewhat to the clustering of CNGVs. The EIA (2008a) listed a CNGV count of 113,973 as of 2008, with the largest number in California (35,980 vehicles), followed by Texas (11,032 vehicles), Arizona (10,072 vehicles), and New York

TABLE 3.16 Long-term Future Natural Gas Prices (\$/million Btu) Forecasted by the 2011 *Annual Energy Outlook*

	2010	2020	2035	2050 (extrapolated)
Commercial natural gas	8.91	8.95	10.98	13.02
Industrial natural gas	4.80	5.36	7.2	9.06
Vehicle natural gas	13.94	14.24	16.81	18.80
in \$/gge	1.69	1.73	1.96	2.18

SOURCE: Data from EIA (2011a).

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[21] In 2011, the quarterly average price ranged from \$3.37 to \$3.69/gal for gasoline and from \$2.06 to \$2.13/gge for natural gas (DOE-EERE, 2011b,c,d; 2012b).

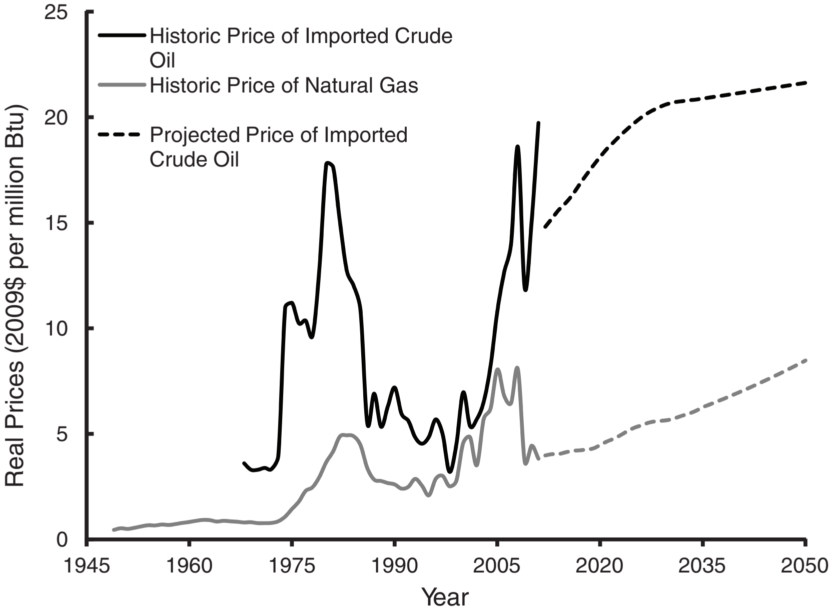

FIGURE 3.5 Historic and projected prices of natural gas and imported crude oil.
NOTE: The prices from 2035 to 2050 were projected by extrapolating the 2030-2035 annual growth rate in EIA (2011a).
SOURCE: Data from EIA (2011a,b).

(10,017 vehicles). The regional clustering of CNG filling stations as a practical model for infrastructure build-up matches the results of models for the clustering of hydrogen filling stations for FCEVs and of public charging stations for BEVs.

CNG prices vary regionally and locally. According to the DOE's Alternative Fuels and Advanced Vehicles Data Center (DOE-EERE, 2011b), average CNG prices per unit gallon of gasoline-equivalent in April 2011 ranged from $1.39 to $2.41 ($2.41 in the Central Atlantic, $2.38 in New England, $2.32 on the West Coast, $1.87 in the Lower Atlantic, $1.84 in the Gulf Coast region, $1.66 in the Midwest, and $ 1.39 in the Rocky Mountain region).

Environmental standards, construction permits, labor costs, natural gas and gasoline costs, vehicle and population density, purchasing power and customer preferences, proximity to natural gas pipelines, the corresponding industrial and commercial natural gas prices, and a host of other factors vary with individual cities, counties, states, and regions, all of which have some effect on the actual and potential extent and rate of penetration of CNGVs. Because of the recent discovery of the U.S. abundance of natural gas, the subject of regional differences needs to be further examined.

3.5.4 Safety of Natural Gas and Compressed Natural Gas Vehicles

Natural gas has a narrow flammability range, which is between 5 and 15 percent by volume in air. Natural gas is lighter than air, and so a gas leak disperses quickly. Unlike gasoline, natural gas will not cause a combustible liquid spill. Its high autoignition temperature means that natural gas does not easily self-ignite on hot surfaces below 540°C,a property quoted as another safety factor in its favor.

CNGVs meet the same safety standards as gasoline and diesel vehicles, and they also meet the National Fire Protection Association's Vehicle Fuel System Code. CNG tanks meet DOE and other government safety standards and have been certified for that purpose. The Clean Vehicle Education Foundation has published a Technology Committee Bulletin (Clean Vehicle Education Foundation, 2010) that provides a detailed treatise of safety considerations for CNGVs. The Clean Vehicle Foundation actually stated that CNG-powered vehicles are considered to be safer than gasoline-powered vehicles.

The DOE has detailed safety analysis and operating recommendations for natural gas filling stations. Properly designed, maintained, and operated facilities for CNG refueling appear to represent no undue safety problems to the public.

3.5.5 Barriers

Public policies at various government levels have not kept up with the increased abundance of natural gas in the United States and are expected to develop rapidly in the coming years.

The CNG infrastructure (filling stations, gas distribution) is in its early stage of development and requires massive expansion. Regional, clustered development will remain the preferred model.

Finding: With increasing economic natural gas reserves and growing domestic natural gas production mostly

from shale gas, there is enough domestic natural gas to use within the transportation sector without significantly affecting the traditional natural gas markets. The opportunities include producing electricity for PHEVs, producing hydrogen for FCEVs, and using as a fuel in CNGVs.

Finding: CNG used as a transportation fuel is an important near-term transition opportunity that could be exploited because of its ability to economically replace petroleum and to reduce GHG emissions from the LDV fleet.

3.6 LIQUID FUELS FROM NATURAL GAS

3.6.1 Current Status

The production of liquid fuels—diesel, gasoline, or a combination of both—from natural gas has been practiced commercially since the early 1980s. As in the case of coal, the first step in the GTL process is the conversion of natural gas into a mixture of carbon monoxide and hydrogen (synthesis gas). There are two options for using this synthesis gas to produce liquid fuels. One is the production of methanol followed by the conversion of methanol into gasoline (MTG). The other option is the conversion of the synthesis gas via FT chemistry to a broad range of paraffinic hydrocarbons. The hydrocarbon molecules with more than 20 carbons are then hydrocracked into molecules in the diesel (15-20 carbons) and naphtha (6-12 carbons) range. The quality of the diesel fuel is excellent but the naphtha has a low octane value and has to be further processed to be used as gasoline (NAS-NAE-NRC, 2009b).

For nearly 10 years in the 1980s, Mobil Corporation operated a facility in New Zealand that produced gasoline by the MTG process (ExxonMobil, 2009). Today, the facility makes only methanol for chemical use (Tabak, 2006) because converting the methanol to gasoline is not viewed as economical at current gasoline prices. Shell has produced diesel fuel and lubricants since the late 1980s in a facility in Malaysia via FT chemistry and Shell is building a plant in Qatar, based on the same process chemistry. That facility is expected to eventually produce more than 140,000 barrels of diesel fuel per day (Kingston, 2011). Another facility in Qatar that is smaller (about 34,000 bbl/d) and based on the same FT chemistry is coowned by Sasol, Chevron, and the Government of Qatar. Similar facilities have been proposed for gas-rich locations such as Nigeria (Chevron, 2011).

3.6.2 Capabilities

The conversion of natural gas into synthesis gas is significantly simpler when compared to the production of synthesis gas from coal. At present, the preferred pathway uses what is called an auto-thermal reactor (ATR). In an ATR, a portion of the natural gas (methane) is burned with oxygen into CO_2 and water vapor. This reaction is highly exothermic (that is, it releases heat) and results in a mixture of CO_2, unreacted methane, and steam at temperatures close to 2,000°C. This mixture is converted into carbon monoxide and hydrogen in a fixed bed containing a nickel-based catalyst. Although ATRs are very efficient and compact, the design and operation of the feedstock and burner system requires careful attention to the mixing of oxygen, steam, and methane (Haldor Topsoe, 2011).

The processing steps are significantly less complicated than in a coal plant. The natural gas, if needed, is cleaned of sulfur compounds before being fed to the ATR. Because methane has four hydrogen atoms for each carbon atom, the synthesis gas from the ATR has the required ratio of two molecules of hydrogen per molecule of carbon monoxide. Thus, the synthesis gas can be used without further processing to produce either methanol or FT hydrocarbons followed by the conversion of these into gasoline or a diesel/naphtha mixture as discussed above.

3.6.3 Costs

The data presented in Table 3.17 were derived from a report prepared for the Alaska Natural Resources to Liquids LLC and requested by the Alaska legislature (Peterson and Tijm, 2008). The results of that study were in good agreement with data published by various companies (Shell, Sasol, and ExxonMobil) on GTL technology performance and economics.

As in the case of CTL, this committee assumes that the GTL plants built later will benefit from a learning curve. Therefore, the estimated investment required was $5 billion for a 2020 facility, $4 billion for a 2035 facility, and $3 billion for a 2050 facility. These investment costs do not include CCS. Although CCS could be used in a GTL facility, the amount emitted from a GTL facility is significantly less than that for similar-size CTL facilities. Therefore, CCS was not included in GTL facilities for the purpose of this study.

TABLE 3.17 GTL Outlook Process Data

GTL/MTG	2020	2035	2050
Gas, million scf/d	400	400	400
Fuel production, bbl/d	50,000	50,000	50,000
Investment, $billion	5.0	4.0	3.0
Product cost, $/bbl	103.5	106.0	109.0
CO_2e produced by the process, metric tons/d	3,840	3,840	3,840
CO_2 vented, metric tons/d	2,110	2,110	2,110
CO_2 stored, metric tons/d	—	—	—

NOTE: Product cost basis: (1) 20 percent of capital annual charge (financing, return on capital, maintenance), 90 percent capacity utilization; (2) natural gas prices as per AEO 2011 (EIA, 2011a), $5.36/million cubic feet for 2020, $7.21/million cubic feet for 2035 and $9.06/million cubic feet in 2050; (3) CO_2e emissions from gas production are based on GREET estimates for the production and transport of gas.

The cost estimates for GTL are based on the FT process economics (see Table 3.17). There are no published data available for the MTG option. For the purpose of this study, capital cost and overall performance data for the MTG option are expected to be similar to the numbers presented in Table 3.17. The investment required for the GTL processes is lower than the investment estimated for the CTL options. This is expected because CTL requires the greater complexity of coal gasification and the complex cleaning of the synthesis gas, and because of the fact that half of the coal has to be converted to CO_2 (to make hydrogen), which in turn has to be captured and stored (CCS).

The cost for the liquid fuel from a GTL plant is about \$106/bbl in 2035, which is less than the price of crude oil in 2035 (\$125/bbl) forecasted by EIA (2011a). However, the GTL cost estimate is based on a natural gas price of \$7.21/million cubic feet in 2035, which is lower than natural gas prices in 2008 and earlier. If the price of natural gas were to reach \$10.0/million cubic feet, the liquid product cost would increase to \$130/bbl. The cost of the liquid product in 2050 is estimated at \$109/bbl based on a natural-gas price of \$9.06/million cubic feet. If the natural-gas price were \$11.0/million cubic feet, the liquid-product cost escalates to close to \$130/bbl.

3.6.4 Implementation

GTL technology has been commercialized in a number of locations where the price of natural gas is low because those locations are far away from markets where the gas can be used directly for power and heat generation. Moreover, all the GTL facilities are based on producing diesel fuel, naphtha, and in some cases high-value lubricants.

When considering the application of GTL technology in the United States, two factors need to be considered. First, the MTG option might be preferred because gasoline is a more widely used transportation fuel than diesel. Second, the price of natural gas will likely be significantly higher in the United States than in other areas of the world where it is readily available (e.g., in the Middle East and in West Africa) because it can be readily used in heating, power generation, petrochemical production, and other industries. The forecasted production of liquid fuels from natural gas (GTL) assuming an optimistic outlook and a more realistic outlook is summarized in Table 3.18.

The estimates for fuel production from GTL are sensitive to natural gas prices. Using the 2011 AEO (EIA, 2011a), the cost of the fuel in 2035 is about \$105/bbl, which is lower than the crude-oil price forecasted for that year. However, a 25 percent increase in the price of natural gas would raise the final-product price well above the crude-oil price.

The GHG emissions for the production of GTL fuel are, as in the case of coal, comparable to the emissions from producing petroleum-based fuels. Thus, GTL without CCS for LDVs reduces the consumption of petroleum-based fuels but does not yield any GHG reduction. Adding CCS to a GTL facility would have a small effect on the life-cycle GHG emissions of the fuel produced because the GHG releases that could be captured at the conversion facility are small compared to the CO_2 release from combusting the liquid fuel.

TABLE 3.18 GTL Outlook Production Estimates

	2020	2035	2050
Optimistic outlook			
GTL/MTG plants	1	4	12
GTL/MTG production, bbl/d	50,000	200,000	600,000
Realistic outlook			
GTL/MTG plants	1	3	6
GTL/MTG production, bbl/d	50,000	150,000	300,000

3.6.5 Infrastructure Needs

Because natural gas is readily available throughout most of the country, there are no major issues with either infrastructure or the location of GTL facilities.

3.6.6 Safety

Although the GTL process includes a complex step for generating synthesis gas, there are no unique safety issues. Natural processing, transmission, and use are widely practiced in the United States. The process of converting natural gas to a liquid fuel for LDVs has many similarities to petroleum-refining processes, and well-known safety practices can be applied.

3.6.7 Barriers

One important barrier to the wide use of natural gas to make liquid fuels is the cost over the life of commercial GTL facilities and the availability of natural gas. Recent technology advances for producing gas from tight shales and other low porosity reservoirs suggest that the natural-gas resources in the United States are significantly greater than previously estimated. The resource availability is a positive factor, but the cost and the environmental impact of producing this tight gas are unclear at present. Moreover, natural gas is used in all sectors of the economy, and the distinct advantage of using natural gas in electricity generation suggests that the demand for gas in this sector could increase dramatically. Use of natural gas directly in LDVs is also being proposed. (See Section 3.5 ,"Natural Gas as an Automobile Fuel.") The balance between supply and demand for natural gas in the United States depends on the level of consumption in many sectors and the level of production. Therefore, predicting the future price of natural gas is difficult. Because the cost of the gas feedstock is a major factor in the cost of the GTL fuel made, the estimate for total liquid fuels produced from natural gas in 2050 is less than 600,000 bbl/d in the optimistic case. That production level requires an annual consumption of 1.6 tcf of natural gas, or about 8 percent of the present production in the United States.

3.7 LIQUID FUELS FROM COAL

3.7.1 Current Status

Liquid fuels, both gasoline and diesel, have been produced from coal at a significant scale since the 1930s. At present, the CTL facilities with the largest capacity are in South Africa and produce more than 100,000 bbl/d of liquid products. Moreover, a number of proposed facilities are being considered in China.

There are two technology options for the production of liquid fuels from coal: direct and indirect liquefaction. The direct liquefaction of coal involves reacting coal with hydrogen or a hydrogen-donating solvent. This technology option has been the subject of research, development, and pilot-scale demonstration since the late 1970s. The consensus view is that this technology is still in development and that the complexity of the process scheme and the poor quality of the liquid products are major limitations. However, a demonstration facility was built in China, and that facility may provide a definitive assessment of the coal-to-liquid fuels option (NMA, 2005; NPC, 2007; NAS-NAE-NRC, 2009b).

This section focuses on the indirect liquefaction option that involves the gasification of coal to a mixture of carbon monoxide and hydrogen (synthesis gas) followed by the conversion of this gas into liquid products. There are two schemes to make the synthesis gas into liquid-fuel products. One option is to convert the synthesis gas into methanol followed by MTG (Zhao et al., 2008). The second option is to convert the synthesis gas into a broad range of hydrocarbons via FT chemistry followed by the hydrocracking of the molecules with more than 20 carbons into shorter-chain molecules. The FT option results in a mix of liquid products that includes mostly diesel fuel and a significant amount of naphtha that can be upgraded to gasoline.

The commercial-scale facilities in South Africa are producing diesel and gasoline from coal by the FT option. Although the Mobil Corporation operated a facility that used the MTG option, the feedstock was natural gas rather than coal.

In the report *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (NAS-NAE-NRC, 2009b), a process scheme labeled coal-and-biomass to liquid fuel (CBTL) is proposed. The process uses a separate gasifier for the coal and the biomass feedstocks. The effluents from these gasifiers undergo a number of separation steps to remove solid and gaseous impurities. The biomass gasifier effluent also includes a thermal cracking step to convert the tar produced from the biomass to lighter products. The clean-up streams are then combined and undergo the required processing steps to make liquid products from carbon monoxide and hydrogen and remove and compress the CO_2.

A number of cases presented in NAS-NAE-NRC (2009b) include or exclude CCS, and in other cases the proposed facility produces significant amounts of electric power (these are called once-through cases). Although interesting synergies have been identified in these schemes, all process schemes require different gasification reaction systems for the coal and for the biomass. They can be viewed as requiring a separate CTL and BTL gasification plants in a given site. The number of sites in the United States where there are significant amounts of biomass and coal for commercial-scale facilities might be small.

The potential benefits of combining the gas products from the biomass and coal gasification to make liquid fuels and electric power are clear from the studies available. A CBTL facility produces liquid fuels at a higher cost than does a CTL facility but at lower cost than a BTL facility. Moreover, by capturing the CO_2 produced in the biomass portion of the facility, the process drastically reduces the life-cycle GHG emissions of the liquid fuels (the emissions during their combustion are counterbalanced by the CO_2 taken up during plant growth). The potential benefits of CBTL facilities, while significant, will require commercial-scale demonstrations of BTL technology and combining it with CTL technology.

The CBTL process was not included in the case study model runs explained in Chapter 5 because it is a derivative process of two commercially available processes. Coal conversion and biomass conversion to liquids are individually included in all of the model scenarios.

3.7.2 Capabilities

The United States has ample coal resources that can allow the production of significant amounts of liquid fuels such as gasoline and diesel from coal. Most coal produced in the United States (about 1 billion tons per year) is used to generate electricity. In principle, additional coal could be mined to produce liquid fuels because the coal reserves in the United States are estimated to be in the range of 250 billion tons. However, concerns have been raised about the environmental impact of coal mining and of the disposition of mineral ash present in coal. Those concerns apply to all uses of coal (AAAS, 2009; EPA, 2011a,b).

The process to convert coal into a liquid fuel is complex and expensive. The gasification of the coal is the most challenging process step. The coal has to be fed into a reactor that operates at pressures ranging from 20 to 50 atmospheres along with pure oxygen and water. The average reactor temperature is about 800°C. Because coal is a solid and its quality varies, the feed system is complex and sensitive to the coal quality. Moreover, coal contains a number of impurities including mineral ash, sulfur, nitrogen and mercury. A number of process steps are needed to remove the byproducts of the gasification reaction to yield a pure stream of carbon monoxide and hydrogen (KBR, 2011).

The second major challenge in making liquid fuels from coal that applies to both the FT and the MTG options is the fact that chemistry dictates that two molecules of hydrogen react with one molecule of carbon monoxide. Because coal, on average, contains only an atom of hydrogen per atom of carbon, half of the carbon monoxide produced in the gasification step has to be used to make additional hydrogen. This is done using the water gas shift reaction where water and carbon monoxide are converted into carbon dioxide and hydrogen. Thus, this reaction step yields the required 2:1 mole ratio of hydrogen to carbon monoxide needed for the subsequent reaction steps and also produces one molecule of carbon dioxide for each molecule of carbon monoxide. In other words, half of the coal is converted to CO_2 and the other half into the reactants needed for the next process steps. Therefore, CCS is necessary if coal is to be used to make liquid fuels with life-cycle GHG emissions in the range of those from use of petroleum-based fuels. Although there are a few facilities that use CCS, there is consensus that a large-scale demonstration in a variety of geological formations is required before CCS can be deemed commercially acceptable.

The conversion of carbon monoxide and hydrogen via MTG or FT to diesel or gasoline presents less of a technology challenge and, has been done commercially for many years (ExxonMobil, 2009; NAS-NAE-NRC, 2009b). Most of the commercial facilities have used or are using natural gas rather than coal as the feedstock. The use of natural gas to make liquid fuels is discussed in a separate section above in this chapter.

3.7.3 Costs

The data presented in Table 3.19 are derived from *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (NAS-NAE-NRC, 2009b), which describes in detail the process schemes briefly reviewed here. It also described the challenges and potential of the various technology options. It includes estimates of the capital and operating costs for CTL facilities.

Here, the cost of the first CTL facility built by 2035 has been estimated to be 20 percent higher than the facilities built later on. The MTG facility is estimated to be lower in capital cost and to require less coal for the same level of production of 50,000 bbl/d of liquid-fuel product than would the FT process. The MTG process is more selective than the FT process as indicated by the higher energy conversion efficiency. Efficiency is the percent of the energy content of the coal that is contained in the liquid produced. The efficiency in the 50 percent range indicates that close to half of the coal has to be converted into CO_2. That amount of CO_2 has to be "stored" via CCS in both cases. The capital cost estimated for a facility with a 50,000 bbl/d capacity is high and thus has a major impact on the cost of the liquid-fuel product.

TABLE 3.19 CTL Outlook Process Data

CTL/FT	2020	2035	2050
Coal, tons/d	26,700	26,700	26,700
Fuel production, bbl/d	50,000	50,000	50,000
Investment, $billion	6.0	6.0	5.0
Product cost, $/bbl	126.8	122.5	104.7
CO_2 coal production, metric tons/d	2,580	2,580	2,580
CO_2 vented, metric tons/d	5,011	5,011	5,011
CO_2 stored, metric tons/d	29,208	29,208	29,208

CTL/MTG	2020	2035	2050
Coal, tons/d	23,200	23,200	23,200
Fuel production, bbl/d	50,000	50,000	50,000
Investment, $billion	5.0	5.0	4.0
Product cost, $/bbl	105.2	102.5	86.0
CO_2 coal prod, metric tons/d	2,243	2,243	2,243
CO_2 vented, metric tons/d	5,520	5,520	5,520
CO_2 stored, metric tons/d	23,280	23,280	23,280

NOTE: Product cost basis: (1) 20 percent of capital annual charge (financing, return on capital, maintenance), 90 percent capacity utilization (2) $50/metric ton of CO_2 pipelined and stored underground in 2020, $40 in 2035, and $30 in 2050; (3) coal prices as per AEO 2011 (EIA, 2011a), $1.85/million Btu in 2020, $1.98 in 2035, and $2.00 in 2050; (4) CO_2 emissions from the coal production are based on GREET estimates for the production/transport of coal.
SOURCE: Data from NAS-NAE-NRC (2009b).

The cost of the liquid-fuel product made in the CTL facilities is within the range of the cost of a barrel of crude oil forecasted for 2035 in the 2011 AEO (EIA, 2011a) and the cost of a barrel of crude oil extrapolated to 2050. However, the CTL estimate is based on a coal price that remains essentially constant from the 2009 price; a doubling of the coal price will yield product costs of over $150/bbl. Conversely, coal prices could decrease as a result of increasing use of natural gas or other resources for electricity generation. The CTL facilities take a long time to build, and thus their payback requires high product prices for a long period of time.

3.7.4 Infrastructure Needs

The process cost estimate for CTL is based on the facilities using Illinois #6 coal and the CTL plants being built in the Midwest. Therefore, the mining and transport of the coal to the CTL facilities are assumed to be handled within the present infrastructure. The liquid-fuel products from the facilities will be consumed in the Midwest and will be marketed using the present infrastructure. The CO_2 is assumed to be pipelined and stored underground within a 150-mile range because geological studies indicate a significant storage potential in the Illinois Basin (Finley, 2005). Therefore, the main new infrastructure needed will be the pipelines to transport the CO_2, the injection wells to store it in underground formations, and the equipment to monitor CO_2 emissions in the pipelines and from the underground storage formations. All of these costs are included by adding \$50/metric ton of CO_2 stored in 2020, \$40/metric ton of CO_2 stored in 2035, or \$30/metric ton by 2050 to the product cost.

3.7.5 Implementation

As mentioned above, CTL technology is used in South Africa at present. The main reason for its commercialization was the need to provide liquid fuels in a country rich in coal. Another major consideration was the embargo of crude oil and petroleum products imposed on the country because of its Apartheid Policy. Economic considerations were, therefore, secondary. While a number of feasibility studies on CTL have been announced in the last 10 years, none of the facilities have reached commercialization. China has been operating a CTL demonstration project (China Shenhua Coal to Liquid and Chemical Co. Ltd., 2010; Reuters, 2011).

There are major barriers to the widespread commercialization of CTL technology. First, the process is complex and costly. Second, large amounts of CO_2 generated by the facilities need to be captured and stored. The process to capture CO_2 is based on the absorption of the gas in a liquid solvent. A number of solvents have been used, and the process is practiced at a commercial scale. It requires a significant amount of energy, thus reducing the efficiency of the overall process. Third, the transportation and storage of CO_2 add to the cost. The gas would be compressed to a pressure of about 125 atmospheres and then pipelined to a region where there is a porous underground formation for storage. Wells will be used to transfer the gas to the formation zone, where the gas is expected to either dissolve in the formation water or be converted to a carbonate salt. In 2011, DKRW Advanced Fuels LLC announced that its subsidiary, Medicine Bow Fuel and Power LLC, entered into a contract to produce liquid fuels from coal and to sell the carbon captured for enhanced oil recovery (DKRW Advanced Fuels LLC, 2011).

Two estimates for the eventual production of liquid fuels from coal are presented in Table 3.20. One is an optimistic estimate, and the other one is a realistic outlook. Both estimates assume that no CTL facilities would be operational in 2020. The technology requires demonstration that large amounts of CO_2 can be captured, pipelined, and stored safely, and such demonstrations are not expected to be completed until later in this decade. Moreover, the design and construction of CTL facilities are expected to take at least 5-6 years for the first few facilities.

TABLE 3.20 CTL Outlook Production Estimates

Optimistic Outlook	2020	2035	2050
CTL/FT plants	—	1	2
CTL FT production, bbl/d	—	50,000	100,000
CTL/MTG plants	—	2	6
CTL/MTG production, bbl/d	—	100,000	300,000
Total production, bbl/d	—	400,000	150,000

Realistic Outlook	2020	2035	2050
CTL/FT plants	—	1	1
CTL/FT production, bbl/d	—	50,000	50,000
CTL/MTG plants	—	2	3
CTL/MTG production, bbl/d	—	100,000	150,000
Total production, bbl/d	—	100,000	200,000

3.7.6 Safety

The actual production of liquid fuels from coal presents the typical safety issues encountered in the handling, gasification, and refining of coal. Thus, CTL safety is expected to benefit from many decades of prior experience. However, there is much less experience with the safety of pipelining and storing large quantities of CO_2 (at least 9 million metric tons per year from one CTL facility). Although 3,900 miles of national CO_2 pipeline infrastructure exist (Dooley et al., 2001) to transport about 65 million metric tons of CO_2 each year for enhanced oil recovery (Melzer, 2012), geologic storage of CO_2 is only in the demonstration phase (NAS-NAE-NRC, 2009b; see Section 3.8, "Carbon Capture and Storage," below in this chapter). The key issue with CCS is to ensure that the CO_2 does not leak from either the pipeline or the formation itself. At concentrations higher than 2 percent in air, CO_2 can asphyxiate humans and animals (Praxair, 2007). Storing CO_2 entails health and ecological risks associated with acute or chronic leaks (NAS-NAE-NRC, 2009b). Clearly, the safety of CCS operations will be a major concern. CCS is being practiced for oil well stimulation in the North Sea, Algeria, and Saskatchewan, Canada, but at a scale much smaller than what is envisioned for a single CTL facility. There are also a number of pilot demonstrations of CTL in the United States (NETL, 2011).

3.7.7 Barriers

An important issue to be considered when estimating the potential supply of CTL liquids is the actual production of coal with its inherent environmental and safety challenges. If only 500,000 bbl/d of liquid-fuel products are to be produced from coal, 85 million tons of coal would have to be mined and transported each year. Locating CTL facilities close to mines would reduce transportation costs. The coal consumption is equivalent to about 10 percent of the U.S. coal production in 2012. There also are environmental and safety issues related to the disposal of coal ash from the coal gasification step. Thus, a major increase in coal consumption to make liquid fuels is not likely.

The most important barrier to the large-scale use of coal to make liquid fuels is the GHG emissions from these facilities. The process eventually yields a liquid fuel for LDVs that has chemical properties substantially similar to those of petroleum-based fuels. Thus, the carbon content of the fuel is the same as the carbon content of petroleum-based fuels. Moreover, the production of CTL fuel with CCS is estimated to emit at least as much CO_2 as the production, transport and refining of the same fuel from petroleum. For CTL fuels to have life-cycle GHG emissions equivalent to those of petroleum-based fuels, an amount of CO_2 equivalent by weight to the weight of the coal used has to be captured and stored. Thus, CTL technology can reduce the amount of petroleum used in LDVs but does not contribute to reducing GHG emissions.

Finding: GTL fuel and CTL fuel with CCS can be used as a direct replacement for petroleum-based fuel. However, the GHG emissions from GTL or CTL fuel are slightly higher than those from petroleum-based fuel. The role of GTL and CTL with CCS in reducing petroleum use will thus be small if the goals of reducing petroleum use and reducing GHG emissions are to be achieved simultaneously.

3.8 CARBON CAPTURE AND STORAGE

3.8.1 Current Status

In carbon capture and storage, CO_2 is captured from various processes, compressed into supercritical conditions to about 125 atmospheres, pipelined, and then injected into a deep (>2,500 ft), porous subsurface geologic formation. Capturing, storing, and transporting CO_2 all have commercial challenges, but, in most cases, the technologies have been demonstrated or are in the demonstration phase. With CCS there are two major options for storage: deep saline formations and enhanced oil recovery.

3.8.1.1 Deep Saline Formations

In the case of a non-hydrocarbon-bearing formation, the CO_2 in supercritical state will be dissolved partially in the subsurface formation's water phase, and the rest will remain in a separate phase. In certain formations, the CO_2 will react over a very long period of time with the solids and form solid carbonates. These are slow reactions, because it takes decades for a significant amount of CO_2 to be converted to a solid carbonate. Experimental work is being conducted to determine the feasibility of extending this concept to storing CO_2 in subsea formations. Currently, demonstrations of deep saline formation CCS of more than 1 million metric tons per year of CO_2 are in progress in a number of locations (Michael et al., 2010). Additional smaller demonstration projects are planned or underway in the United States and other regions of the world (NETL, 2007, 2011).

3.8.1.2 Enhanced Oil Recovery (EOR)

CO_2 can be injected into already-developed oil fields to recover the oil that is not extracted by initial production techniques. Injected CO_2 mixes with the oil in reservoirs and changes the oil's properties, enabling the oil to flow more freely within the reservoirs and be extracted to the surface. The CO_2 is then separated from the extracted oil and injected again to extract more oil in a closed-loop system. Once economically recoverable oil has been extracted from one area of a given reservoir, an EOR project operator reallocates CO_2 to other productive areas of the same reservoir. Once all economically recoverable oil has been extracted from a given reservoir, the CO_2 remains within the reservoir and the project is plugged and abandoned.

3.8.2 Capabilities

The capture of CO_2 from a gaseous stream has been practiced commercially for many years—for example, CO_2 has been removed from natural gas produced from reservoirs (Statoil, 2010), and the Weyburn project in Saskatchewan, Canada, has used CO_2 captured from a North Dakota coal gasification facility for EOR (Preston et al., 2005, 2009). EOR uses injection of CO_2 into a oil reservoir to assist in oil production. In the United States, typical EOR uses about 5,000 cubic feet of CO_2 per barrel of oil produced (that is, about 160 lb of carbon produce one barrel of oil, which contains about 260 lb of carbon). Oil and gas reservoirs are ideal geological storage sites because they have held hydrocarbons for thousands to millions of years and have conditions that allow for CO_2 storage. Furthermore, their architecture and properties are well known as a result of exploration for and production of these hydrocarbons, and infrastructure exists for CO_2 transportation and storage.

To calculate the largest amount of CO_2 that could be stored by EOR, all the CO_2 used is assumed to remain in the ground. The United States produces about 281,000 bbl/d of crude oil using CO_2 EOR (Kuuskaraa et al., 2011). Based on the best-case scenario for CO_2 use in EOR, this would sequester 0.26 million metric tons per day of CO_2. If all U.S. crude oil was produced by EOR, about 2 million metric tons of CO_2 could be stored per day.

The typical process for capturing CO_2 is by contacting the gaseous stream with a solvent that absorbs the CO_2. A number of solvents have been used. The CO_2 is then desorbed as a concentrated gas and the solvent reused. This process is widely used for processing natural gas streams but much less used with gaseous streams from coal gasifiers or coal combustion units. The key concern is the degradation of the solvent by coal-derived impurities in the process gas. Other processes are being considered and developed to reduce the cost and energy consumption required.

CO_2 compression to about 125 atmospheres for transport and injection is straight forward but consumes a significant amount of energy. High-pressure compression is desirable because it reduces the volume of gas being pipelined, and the supercritical state facilitates injection and retention of the CO_2 (IPCC, 2005).

Pipelining of CO_2 is another conventional and proven step. The key concern is leakage of CO_2 into the atmosphere. An asphyxiant denser than air, CO_2 tends to stay close to the ground and is not easily dispersed. CO_2 is fatal at high concentrations and detrimental to humans at lesser concentrations (Praxair, 2007). Thus, properly designed CCS facilities will include a CO_2 monitoring system and a leak-prevention system.

Specially designed injection wells are required for CCS. Abandoned oil and gas wells will not be used for CO_2 injection into spent oil and gas formations because these wells may not be capable of handling the acidic supercritical CO_2, and they may not be properly cemented to ensure that CO_2 does not leak into aquifers used for drinking water.

3.8.3 Costs

The cost of CO_2 capture is \$30-\$40/metric ton of CO_2 for a coal gasifier process stream, about \$90/metric ton for a natural gas combined-cycle facility (because of a lower concentration of CO_2 compared to coal gasification), and \$70-\$80/metric ton for coal-fired power facilities (IPCC, 2005). Adding in the cost of compression, pipelining, monitoring and injection into a suitable formation would increase the total cost by \$30-40/metric ton (IPCC, 2005). For most CTL facilities, the cost of CO_2 capture is included in the facility design and construction cost. However, additional costs are incurred for compression, pipelining, monitoring, injection, and storage. These costs are estimated at \$40/metric ton of CO_2 in the first-mover facilities (2035 timeframe) and \$30/metric ton in facilities built later (2050 timeframe). In cases of CTL where the costs of capture are to be included, \$80/metric ton of CO_2 for 2035 and \$70/metric ton of CO_2 for 2050 are used.

3.8.4 Infrastructure Needs

CCS requires a large infrastructure—primarily the construction of pipelines to transport the CO_2 from where it is captured to injection wells for storage underground. In the United States, potential reservoirs with a capacity for storing more than 100 years' worth of injected CO_2 are available within 100-150 miles of expected sources in most regions of the country (NACAP, 2012).

3.8.5 Barriers

The cost of CCS is significant but probably not the major implementation barrier. The major barrier is the public acceptance of pipelines, injection wells, and storage of large amounts of carbon dioxide in subsurface formations (Court et al., 2012; de Best-Waldhober et al., 2012; Kraeusel and Moest, 2012), especially if these are near population centers. Leakage of stored CO_2 is an issue that is still being investigated through research programs conducted by industry and DOE. Careful design and operation of CCS can likely prevent and mitigate any potential emissions of CO_2, but gaining public acceptance is expected to be difficult given the large quantities of CO_2 to be transported and stored. A single CTL facility producing 50,000 bbl/d of liquid fuels will require CO_2 storage in the range of about 4 million to 9 million metric tons per year.

Finding: CCS is a key technology for meeting the study goals for GHG reductions by 2050. It will be very difficult to make large quantities of low-GHG hydrogen without CCS being widely available. Combining CCS with biofuel production would improve the chances of meeting the study goals.

3.9 RESOURCE NEEDS AND LIMITATIONS

Reducing petroleum consumption and GHG emissions from the LDV fleet will have a significant impact on energy resource use in the United States. Comparing existing resources with the estimated demands on resources for fueling the vehicles in representative scenarios in its analyses, the committee here draws conclusions about whether the projected demands on resources can be met.

Alternative LDV fuels can be produced from natural gas, coal, biomass, or other renewable energy sources, such as wind, solar, and hydro power. The U.S. consumption of natural gas, coal, and biomass in 2010 is shown in Table 3.21. Of the amounts consumed, 976 million tons of coal and 7.378 tcf of natural gas were used for electricity generation (EIA, 2011b). The biomass was used primarily for power in wood-processing plants, with some generated electricity going into the grid.

TABLE 3.21 U.S. Consumption of Natural Gas, Coal, and Biomass in 2010

	Consumption in Quads (higher heating value)	Amount Consumed
Natural gas	24.1	23.4 tcf
Coal	22.1	1,050 million tons
Biomass	4.30	269 million tons

TABLE 3.22 Estimated Amount of Natural Gas Required to Fuel the Entire LDV Fleet via Different Fuel and Vehicle Technologies

		Natural Gas Required Annually for Different Vehicle-Fuel Combinations (tcf)					
Year	Vehicle Miles Traveled (trillion mi/yr)	ICE-CNG	ICE-drop-in	ICE-Methanol	HEV-CNG	Electric	FCEV
2010	2.784	15.6	23.8	22.9	15.1	7.6	11.7
2030	3.727	10.1	15.5	14.9	8.4	7.5	7.3
2050	5.048	10.0	15.4	14.8	7.9	7.8	7.2

Biomass, coal, and natural gas can all be converted into "drop-in" liquid fuels by several routes (e.g., direct liquefaction of biomass or coal, and gasification followed by FT or MTG of all sources). These drop-in fuels will use the existing petroleum products distribution system and existing vehicles. The use of any of these alternative fuels would be transparent to the vehicle owner. The remaining alternative fuel and vehicle combinations include electricity in BEVs and PHEVs, hydrogen in FCEVs, and natural gas as a vehicle fuel, either directly as CNG or through conversion to methanol. All of these fuels can be produced from natural gas via mature technologies, and so a meaningful comparison would be to calculate the amount of natural gas that would be required to fuel the entire LDV fleet via the different fuel and vehicle technologies (Table 3.22). The vehicle efficiencies are assumed to be the mid-range efficiencies outlined in Chapter 2.

Direct use of CNG as a vehicle fuel is more resource efficient and less costly than conversion of natural gas to any liquid fuel. The advantages of conversion to a liquid fuel are the use of the current fuel infrastructure, the ease of onboard storage, and the familiarity of the driving population with liquid fuels. Conversion of natural gas to electricity or hydrogen as an energy carrier is currently more resource efficient than direct use of natural gas, but direct-use efficiency converges with that for PEVs and FCEVs by 2050 because of the differences in efficiency improvements with time. Both electricity and hydrogen carry additional socioeconomic burdens and infrastructure costs as discussed in previous sections. Electricity and hydrogen, as well as GTL and methanol, can be produced from other resources such as coal and biomass. Electricity and hydrogen can also be produced from nuclear, solar, and wind power.

There are two distinct goals for the scenarios evaluated by the committee: one goal targets only petroleum reduction, and the second goal targets reduction of GHG emissions. Both cases use the same vehicle and fuel technologies; however, in the low-GHG cases, the technology and fuels used to generate electricity and hydrogen were modified to reduce GHG emissions. The driving force for the low GHG grid case is discussed above in this chapter. Table 3.23 shows the impact of the low-GHG grid case on the mix of generating sources.

TABLE 3.23 Effect of the Low-Greenhouse Gas Grid on the Mix of Generating Sources

	Total Generation (billion kWh/yr)		
	2009	2050 Reference Grid	2050 Low-GHG Grid
Coal without CCS	1,693	2,368	238
Coal with CCS	0	15	17
Petroleum and natural gas without CCS	871	1,290	1,225
Petroleum and natural gas with CCS	0	0	489
Nuclear	795	855	1,255
Hydroelectric	274	314	323
Biomass	38	159	179
Solar	3	21	56
Wind	71	163	330
Other	34	66	66

The largest changes between the reference grid and the low-GHG grid are an almost 90 percent decline in coal usage, a doubling of natural gas, and a 50 percent increase in nuclear power. Total renewable electricity increases by over a factor of two and rises from 11 percent of total generation to 23 percent.

Table 3.24 shows the fuel usage and resource demands for 10 scenarios: five different vehicle mix scenarios, compounded with the reference grid and the low-GHG grid case and two different resource mixes for producing hydrogen.[22] The implementation of these cases would be driven by various government policies. The reference case scenario is driven by existing and currently proposed policies for LDV CAFE standards and RFS2. The other cases stress increased biofuels, PEVs, FCEVs and CNGVs.

These scenarios have not been optimized to minimize costs, resource use, or GHG emissions. The reference scenario reduces petroleum use by 25 percent, and the others all meet or exceed the goal of an 80 percent reduction in petroleum use. GHG emission reductions are all similar for the reference-grid scenarios. Additional reductions in GHG emissions are possible for the electric and hydrogen cases

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[22] These scenarios are described in greater detail in Section 5.3.2.

with the use of a low-GHG grid and a change in the mix of resources used to generate hydrogen. Only the FCEV scenario meets the goal of reducing GHG emissions by 80 percent in 2050. The biofuel case can also meet the GHG emissions target if CCS is added to the biorefineries.

The resource demands can be met but involve some challenges. The largest changes are needed to achieve a low-GHG grid. These include an increased use of almost 7 tcf/yr of natural gas (a doubling of the current consumption for electricity), the construction of about fifty 1,000-MW nuclear power plants and about 100,000 new wind turbines and the capture and storage of more than 200 million metric tons/yr of CO_2.

The most challenging related demands concern increased use of biomass and natural gas and public acceptance of the construction of a large number of nuclear power plants. As discussed above in this chapter, the demand for biomass is expected to be achievable and to be less than the biomass availability estimated in other recent analyses. Shipping and handling the mass and volume of biomass involved will be challenging. Natural gas demand doubles over the amount currently used to generate electricity. This increase represents essentially all of the additional natural gas expected to be available for use based on the most recent estimates of future gas availability in the United States.

There are important ancillary impacts from these resource demands on the associated infrastructure:

- Cleaning up the electric grid by 2050, as envisioned in 2011 AEO (EIA, 2011a), the basis for this discussion, will reduce current coal use by 85 percent or about 800 million tons per year, an amount that represents 44 percent of the total annual U.S. railroad freight tonnage. Shipments of biomass could mitigate that impact.
- Most petroleum products are currently shipped long distances by pipeline. Significant increases in hydrogen or electricity as an LDV fuel would idle a large fraction of the petroleum pipeline system.
- The large increase in natural gas consumption would require a significant expansion in natural gas pipelines. Use of hydrogen as an LDV fuel would require construction of an additional hydrogen pipeline system.
- CCS has to be economical and meet stringent performance requirements at large scale. CCS demonstrations at appropriate scale are needed to validate performance, safety, and costs.

Nearly 50 percent of U.S. petroleum refining output is currently used to fuel the LDV fleet. An 80 percent reduction in use of petroleum for LDVs will impact the availability and price of the refining byproducts that are used by other industries.

TABLE 3.24 Fuel Demands for Illustrative Scenarios and Resources Used

Scenario	2005 Actual	Reference	Biofuels	Electric	FCEV	CNG
Petroleum based fuels, billion gge/yr	124.8	93.1	17.2	13.9	3.8	4.1
GTL and CTL, billion gge/yr	0	7.7	7.7	7.7	0.8	0.8
Total biofuels, billion gge/yr	4.9	24.1	55.9	24.1	19.2	19.1
Electricity, billion gge/yr	0	1.3	0	14.4	1.6	1.0
Hydrogen, billion gge/yr	0	0.5	0	1.1	33.5	0.5
CNG, billion gge/yr	0.1	0.1	0.1	0.1	0.1	51.0
Petroleum reduction, %		25.4	86.2	88.9	97.0	96.7
Ethanol, % of liquid fuels	5.6	11.9	17.5	30.9	30.7	33.9
Resources Used to Power Vehicles, Reference Electric Grid						
Corn, million tons/yr	81	165	165	165	84	99
Other biomass, million tons/yr	0	208	703	220	325	208
Natural gas, billion cubic ft/yr	18	1,021	888	1,915	3,038	6,969
Coal, million tons/yr	0	50	39	150	108	14
Net GHG emissions reduction, %	—	11	67	55	60	56
Resources Used to Power Vehicles, Low GHG Electric Grid and Hydrogen Production						
Corn, million tons/yr	81	165	165	165	84	99
Other biomass, million tons/yr	0	209	703	226	358	209
Natural gas, billion cubic ft/yr	18	1,105	890	2,613	4,664	7,039
Coal, million tons/yr	0	41	39	54	15	6
Net GHG emissions reduction, %	—	13	67	72	85	58

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4

Consumer Attitudes and Barriers

The preceding chapters demonstrate that there is great potential for new generations of advanced-technology vehicles, fuels, and fueling infrastructure to advance the nation toward the twin goals of significantly reducing greenhouse gas (GHG) emissions and petroleum use from the light-duty vehicle (LDV) fleet by 2050. But technological advances alone are insufficient to promote success. Consumers must embrace the new designs and new fueling systems discussed in Chapters 2 and 3, or LDVs and fuels will never achieve the market penetration rates necessary for successful achievement of the petroleum and GHG reduction goals of this study. While highly efficient internal combustion engine vehicles (ICEVs) and "drop-in" biofuels would differ little in most characteristics that consumers consider (other than cost), alternative-fuel vehicles (AFVs) operating on electricity or hydrogen will appear very different to consumers. Given that most of these vehicles will come with a so-called technology premium that, initially at least, will make them more expensive than the vehicles they will seek to replace, winning consumer acceptance will be challenging, likely requiring substantial policy intervention.

Consumer purchasing patterns have been studied for decades. Although many vehicle attributes influence car-purchasing decisions (Box 4.1), the common conclusion is that buyers' economic concerns are one of the primary drivers of almost all transactions (Caulfield et al., 2010; Egbue and Long, 2012): money talks; most of the rest is window dressing. Thus, when dealing with the task of selling vehicles whose primary purpose is to help reduce petroleum consumption and the related environmental impacts, appeals to consumers' environmental and social sensibilities are not likely to move much metal after the thirst of the relatively small groups of innovators and early adopters is satiated.

Attracting members of these two groups, part of a hierarchy established by Everett Rogers in his seminal *Diffusions of Innovations* (Rogers, 1962), is critical, however. Rogers (2003) estimated that they collectively make up just 16 percent of the consumer base, but their acceptance or rejection of innovations guides the remaining consumer groups. They set the stage by removing uncertainty about new products, policies, or technologies and by establishing a level of peer acceptability that makes more risk-adverse consumers comfortable with accepting them as well.

The initial group, the innovators, is the smallest, estimated by Rogers at just 2.5 percent of the consumer base. Their role is to launch new ideas, products, and technologies. They typically are younger and more financially sound than the general population and are characterized by a desire to be first to possess or use something new and different in the market. They are willing to take risks and can use their financial well-being to soften the impact of the occasional failed venture. Early adopters are the next group to adopt an innovation. They constitute approximately 13.5 percent of the consumer base. The group includes a high percentage of opinion leaders, but

BOX 4.1
Attributes that Could Affect Car-Purchasing Decisions

CO_2 emissions
Comfort
Ease of fueling
Fuel consumption
Initial and operating costs
Performance or power
Reliability
Safety
Size of car or internal and cargo space
Style or appearance or image
Travel range

NOTE: The attributes are listed in alphabetical order.

its members are less risk-averse than the general population and more selective than innovators in their enthusiasm for innovations to adopt. Like innovators, they tend to be younger and have higher income levels and social status than other consumers. Early adopters tend to be opinion leaders in their communities and are in the group most looked-to by other consumers for validation of or information about new things. In the automotive arena, Deloitte Development LLC (2010) characterized early adopters for one combination of alternative vehicle and fuel technologies—the battery electric vehicle—as young individuals with annual household incomes of $200,000 or more who consider themselves to be environmentally sensitive and politically involved.

Not all innovators and early adopters will embrace the same products, ideas, or technologies, so technology and policy developers cannot count on the groups as a monolithic 16 percent of the market. Still policy makers and the private auto and fuel industry companies must work together in pursuit of the nation's GHG and petroleum-use reduction goals. They must be able to attract the interest of a significant portion of these two groups to make inroads with the general consumer base, which Rogers further divided into the early and late majority adopters, each constituting an estimated 34 percent of the consumer base, and the laggards, or last to adopt, constituting the remaining 16 percent of consumers. Rogers determined that innovations achieve peak market penetration with the early majority adopters.

Each of the various groups can be further subdivided into smaller market categories defined by factors such as age, gender, geography, income, social status, and political leanings. Thus, the automotive innovator group might include dedicated environmentalists, older empty-nesters, and "first on the block" ego gratification seekers. The environmentalists would be willing to pay a premium and accept reduced travel range, cargo and passenger capacity, and limited refueling opportunities to acquire vehicles and/or use fuels that they believe would help reduce GHG emissions; the empty nesters might simply wish to free themselves of the expense of purchasing petroleum-based gasoline (and recognize that they no longer need a vehicle that can travel long distances); and the first-on-the-block innovators may simply be those whose egos are gratified by being seen as out in front of the pack in their vehicle choices and whose incomes can support their desires. The success of a new automotive and/or fuel technology or idea will require that the needs of such disparate subgroups be met.

Meeting the needs of all subgroups or selling these new automotive ideas to the early majority will not be easy. Increased utility and convenience cannot be counted on as selling points. The automobile became a successful new technology in the early 20th century because it demonstrated superiority to the horse- and ox-drawn vehicles it would replace. It offered greater speed, greater range, and greater utility than animal-drawn vehicles and promised the individual a new level of freedom of movement (Morris, 2007). With an engine that demanded combustible fuel, the auto also gave the oil industry a whole new market for its product.

If policy makers determine that AFVs are essential to meeting the nation's oil and GHG reduction goals, then consumers will have to be asked to consider adopting another significant change in personal transportation, but it is one that—at least in the formative stages—means sacrifice, not improvement. The contemplated change is not replacing the horse-drawn buggy with a motorized carriage that can carry its own fuel for hundreds of miles and be refueled in minutes. Rather, it is the swapping of a sizeable portion of conventional, internal-combustion LDVs that run on liquid hydrocarbon fuels and the accompanying nationwide system of fueling stations for a variety of new vehicles and fuels that will require development of massive new production, distribution and retailing systems. In addition, many of these new AFVs use powertrains—such as plug-in hybrid electric (PHEV) systems—that typically cost more and offer no improvements other than increased fuel efficiency, reduced emissions, and, in the case of plug-in vehicles, cheaper fuel costs for the electricity used to charge the batteries. Battery electric vehicles (BEVs) offer less range, and along with PHEVs would require large GHG emissions reductions in the electricity production system to deliver meaningful net GHG reductions for the LDV sector. Some options, however, such as the drop-in biofuels described in Chapter 3, entail few if any customer acceptance challenges for the vehicles, which can still use internal combustion engines. In this case, the technology challenges are upstream in the fuel supply sector, with implications for the fuel costs experienced by LDV consumers.

This chapter examines demonstrated results and stated preference surveys, with stated preference surveys in the forefront because, as many of the vehicle and fuel types under consideration are not yet in the market, there has been little opportunity for researchers to conduct studies of demonstrated preferences. The preference surveys, particularly in environmental matters, have a certain level of bias engendered by respondents' wish to appear environmentally responsible even if economic conditions rather than environmental beliefs ultimately determine their actions (Kotchen and Reiling, 2000), but the impact of such biases—which remains unquantifiable (Hensher, 2010)—does not materially affect their value in illustrating general trends over time.

4.1 LDV PURCHASE DRIVERS

There is no big mystery at work in the LDV-buying decision process. Consumers typically acquire things for a range of reasons. In the case of LDVs, research has shown that the bulk of purchases revolve around perceived need—to replace an aging vehicle, for instance. "Desires," whether for a different color or body style, improved "infotainment" content, a more prestigious nameplate, or simply a newer model, still account for a significant minority of purchase decisions,

TABLE 4.1 Car-Buying Motivations, 2005 and 2011

Motivation to Consider Buying New Car	April 2005 (%)	August 2011 (%)
Old car had high mileage	34.3	25.7
Old car needed frequent repairs	17.3	14.3
Needed additional vehicle for family	18.0	11.9
Needed vehicle with more room	12.0	12.3
Lease expired	9.7	9.5
Wanted new vehicle	6.5	8.0
Wanted better fuel economy	21.9	16.7
Not sure/other	18.3	22.4
Liked styling of new models	16.3	12.3
Wanted vehicle with better safety features	14.6	11.5
Financing deals/incentives too good to pass up	13.8	11.7
Significant other wanted new car	17.6	16.1
Wanted car with new infotainment equipment (navigation, DVD player, etc.)	11.8	7.9

NOTE: Sum of totals exceeds 100 percent because respondents could provide multiple responses.
SOURCE: BIG Research, Consumer Intentions and Reactions, April 2005, August 2011, proprietary information prepared for the committee by request.

however. Table 4.1 shows surveys of retail consumers taken in two periods—2005 and 2011—representing different economic conditions.

A large number of LDVs are purchased each year for commercial and government fleets, and those purchases are not reflected in Table 4.1 or in Figure 4.1, both of which examine trends among retail consumers. Yet the fleet segment is one in which a substantial number of AFVs will be sold in the future per private and governmental policies encouraging greater use of highly fuel-efficient vehicles. It is too early to tell how those sales might affect the overall success of any particular AFV or alternative fuel.

As these surveys show, replacing a vehicle for reasons including high mileage (age), the frequency of repairs, expired leases, and/or the perceived need for a vehicle of a different size account for more than half the stated reasons for buying a new vehicle. Reasons stated as "wants" or desires rather than needs ran a close second. The need to acquire a new vehicle because the old one was wearing out remains a strong motivation but has diminished in importance among those who purchase their vehicles as vehicle reliability and quality have improved—providing for longer-lived cars and trucks in our garages. Lessees, of course, replace their vehicles more frequently, and typically for reasons other than age-related wear. But leasing accounts for just 20 percent of the new-vehicle market (Automotive News, 2012). The need or desire for a vehicle with better fuel economy, however, has concurrently increased in importance over the past few decades as primary motivation for new-car purchase. (Note: The decline in stated importance of fuel economy between 2005 and 2011 as shown in Table 4.1, is a result of the unusually high level of importance attached to fuel economy that was shown in the April 2005 BIG Research survey and was spurred by gasoline price increases at the time.) The trend of fuel efficiency rising in importance along with fuel prices

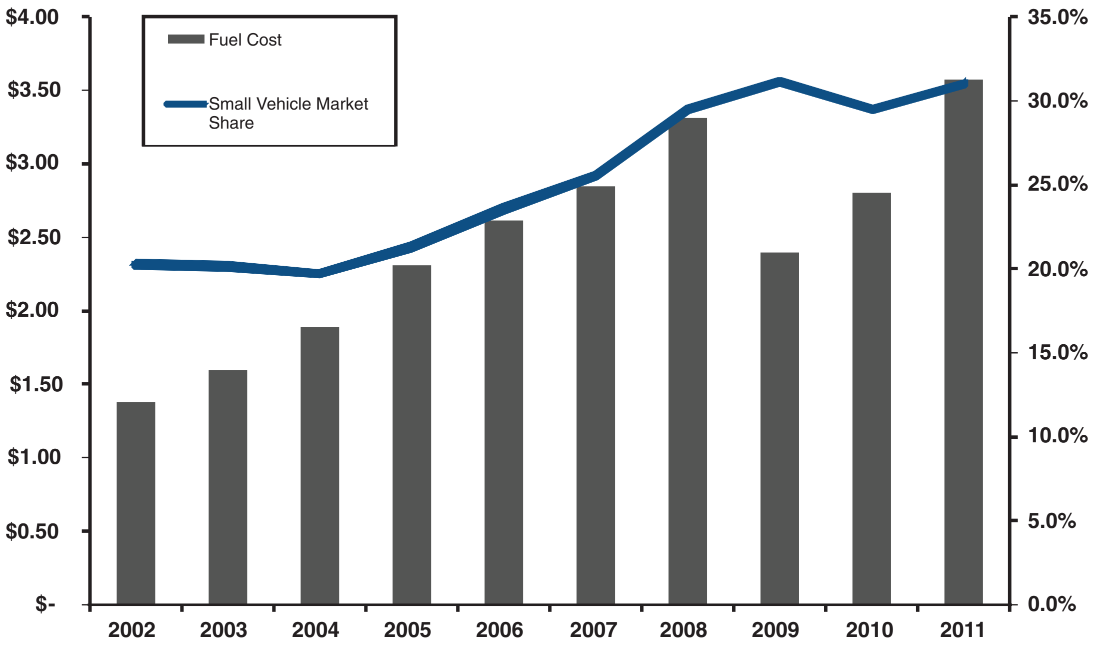

FIGURE 4.1 Small vehicle market share (retail sales only) and fuel cost (in 2011 dollars).
NOTE: Recession-driven sales of less-expensive models helped keep small-vehicle market share high despite fuel price declines in 2009 and 2010.
SOURCE: Data provided by Edmunds.com's AutoObserver.com Data Center; chart prepared for committee by Edmunds.com.

continues: *Consumer Reports* magazine reported recently that in an April 2012 telephone survey of 1,702 adult consumers who were asked to state what they believed would be the most important factors in their next new-car purchase, 37 percent cited fuel economy as their top consideration (Consumer Reports, 2012). While altruistic reasons for purchasing a new vehicle—to help improve air quality, reduce oil use, cut GHG emissions, improve the environment—score highly in some special-interest group surveys (Consumer Reports, 2011b), in broader whole-market surveys that allow respondents to list their own reasons for purchase, they appear, at worst, to be not considered at all or, under the best of interpretations, to be secondary, hidden constituents of the more selfish, economics-driven stated reasons such as "wanted better fuel economy" or "wanted new vehicle." A motivator not mentioned in the surveys cited but known to be a purchase driver of certain AFVs in the state of California is single-occupant access to high-occupancy vehicle (HOV) lanes, also called carpool lanes. Although most states that provide such lanes limit access to vehicles carrying at least two people, California currently permits drivers of most battery electric vehicles, some plug-in hybrids, and all fuel-cell electric vehicles to use the lanes even if there are no passengers in the vehicles when an authorized, state-issued access sticker is displayed. Access to HOV lanes in a state noted for its crowded rush-hour freeway traffic is believed to be an important selling point for those vehicles. Indeed, General Motors has released a television advertisement for its 2013 Volt PHEV that highlights the fact that a specially tuned version of the vehicle qualifies for HOV lane access in California.

Achieving a considerable reduction in LDV fleet GHG emissions and petroleum use through adoption of alternative fuels and powertrains is not likely to be accomplished by appealing to altruism. Once early adopters have made their choices, the remaining 84 percent of consumers are going to have to be persuaded either that the alternative fuels and vehicles offer them an improvement over their present preferences, or that there is a pretty immediate economic benefit to be had in making the switch. Environmental benefits simply do not appear to be a determinant for consumers in large purchases, such as motor vehicles. "Economic concerns are consumers' priority," researchers at the Mineta Transportation Institute have found (Nixon and Saphores, 2011, pp. 10-11).

4.2 WHAT DO CONSUMERS WANT?

Conventional wisdom holds that American consumers want big cars and trucks with large and powerful engines and that fuel economy just is not that important because gasoline and diesel prices in the United States are so much lower than in much of the rest of the world. Those attitudes certainly have shaped U.S. automakers' marketing and product planning agendas for most of the time since World War II. As recently as April 2011, in an editorial in the influential trade journal *Automotive News*, publisher Keith Crain bluntly stated that while the auto industry has responded to rising gasoline prices and increased regulatory demand for better fuel economy with a number of cars that achieve an EPA highway-cycle rating of 40 mpg, "the trouble is, no one wants to buy them" (Crain, 2011). Gloria Bergquist, the Alliance for Automobile Manufacturers' vice president for communications, repeatedly has pointed out that in 2010 a single pickup model—the Ford F150—outsold all 30 gas-electric hybrid cars and sport utility vehicles (SUV)s offered for sale in the United States by mainstream auto manufacturers (Harder, 2011). Those statements reflect consumer choices influenced at least in part by continued low pricing of gasoline. In the past year, however, sales of smaller cars with high fuel efficiency have increased as a percentage of the market, as have sales of larger cars, crossovers, and light-duty trucks that use smaller, more efficient engines to replace "gas guzzler" V6s and V8s (Drury, 2011). History, however, has shown that the march toward efficiency stops when fuel prices have stabilized or dropped after a run-up (see Figure 4.1).

Still, such attitudes may be generational. Most Americans under 40 have now been exposed to smaller vehicles, mainly from the import brands, and, as sales trends show, acceptance of compact cars in the U.S. market is growing. The recession of 2008-2009 and the continued economic slump that has followed certainly have influenced that growth, as have increasing fuel prices in recent years. However, there is evidence indicating that potential savings from fuel efficiency improvements is not a significant factor in consumers' vehicle purchase choices, indicating that consumers are becoming inured to gasoline price increases because they inevitably have been followed by price decreases. (See details in Section 4.6 below.)

4.3 FACTORS IN CONSUMERS' CHOICES

Numerous studies have attempted to quantify the needs and desires that drive LDV-purchase decision making. Their findings are fairly consistent and are exemplified by a recent stated-preference study by Capgemini (2010) that ranked the most important factors gathered from 2,600 online respondents in the United States, Europe, and Asia and found reliability, safety, vehicle price, fuel economy, and the variety and cost of options all in the top 10. Consumers who identified themselves as planning to purchase a new vehicle within the next 15 months were asked to rank the most important factors they would apply to their car-purchase decision making (see Table 4.2).

In addition,, respondents were asked about their interest in so-called green vehicles, and 72 percent of U.S. respondents (versus 57 percent overall) cited fuel economy as the number-one reason they would consider a fuel-efficient petroleum or alternative fuel car or truck. Only 13 percent

TABLE 4.2 Importance of Factors in Consumers' Choice of Vehicle

Factors in Consumer Choice	Percent Respondents Saying Important/ Very Important: Mature Markets	Developing Markets
Brand reliability	89	90
Safety	89	91
Price	86	85
Fuel economy	82	85
Quality of exterior styling	77	84
Quality of interior styling	77	85
After-sales service	71	83
Vehicle availability (take it home versus wait for special order)	71	82
Extra options at no cost	70	74
Features and options	66	79
Low emissions	64	75
Financing at 0% or low %	62	73
Brand name	55	80
Cash-back incentive	46	69
Hybrid or other alternative fuel system	36	66

SOURCE: Capgemini (2010).

of U.S. respondents (versus 23 percent overall) cited making a positive impact on the environment as a significant reason for acquiring an AFV, while just 1 percent (versus. 3 percent overall) said tax credits would be an important factor in their purchase decision (Capgemini, 2010). That contrasts rather sharply with the 46 percent (69 percent overall) who said they would prefer a cash-back incentive. The preference for cash-in-hand at time of purchase versus an end-of-year tax credit has important implications when considering incentive policies.

4.4 SUBSIDIES

Capgemini is not the only one finding that income tax credits, although currently the preferred federal policy for incentivizing AFV purchases via subsidies, may not be the best route to take. A number of studies prepared since hybrid-electric vehicles achieved sufficient market penetration to figure as a potentially valuable tool in the effort to reduce the nation's GHG emissions and petroleum use have found that while subsidies work, those that directly place cash in the hands of the consumer are more effective than those—like income tax rebates—that require the consumer to pay the full price up front and wait until tax time for the subsidy payment (Gallagher et al., 2008; Diamond, 2008; Beresteanu et al., 2011).

In addition to providing immediate gratification, direct rebates, sales-tax credits, or other types of cash subsidies, including subsidies enabling the manufacturer to lower the retail price of the vehicle, would enable consumers to rationalize that the cost of the vehicle is less than its so-called sticker price. When applied to the amount being financed, such direct subsidies lower the monthly payment and can help a greater number of consumers qualify for loans to purchase new AFVs. Tax credits, in contrast, do not affect the qualifying terms or monthly payments for purchasers (although they may be used to lower monthly lease costs, as has been the case with the Chevrolet Volt PHEV and Nissan Leaf BEVs). One argument against tax credits such as the present "up to $7,500" federal credit on BEVS and some PHEVS (depending on battery size) is that they tend to reward higher-income consumers—who arguably are least needful of subsidies—and do not provide the full potential reward for consumers with lower incomes and thus lower tax liabilities.

4.5 ICEVs STILL TOPS

Even in the aftermath of publicity about the possibility of future oil shortages and the need for increased national energy security, gasoline as a fuel is not seen by most car-buying consumers as a negative. Indeed, there is a consensus in consumer preference surveys that unless there is intervention through government policy, internal combustion engines powered by petroleum or a competitively priced drop-in biofuel (if such a fuel is commercialized) are likely to remain the predominant powertrain in LDVs in the United States for decades to come. A sampling of recent studies bears this out.

In its June 2011 report on AFV preferences, the Mineta Institute found that "in general, gasoline-fueled vehicles are still preferred over AFVs," with 36 percent of the study's respondents ranking conventional ICEVs as their first choice (Nixon and Saphores, 2011, p. 1). Hybrid-electric vehicles (HEVs) were second in popularity, with 26 percent of respondents identifying them as their first choice, followed by compressed natural gas vehicles (CNGs) at 13 percent, hydrogen fuel cell electric vehicles (FCEVs) at 18 percent, and BEVs at just 9 percent. The responses exceed 100 percent because each is the average of respondents' choices in a variety of scenarios. A stated-preference survey of 3,000 consumers in the United States, Germany, and China, conducted in the first quarter of 2011 by Gartner, Inc. (Koslowski, 2011), presents similar findings, with 78 percent of respondents ranking gasoline-fueled vehicles as the type they "definitely" would consider for their next new-vehicle purchase, followed by HEVs, 40 percent; CNGVs, 22 percent; and BEVs, 21 percent. Respondents in the Gartner study were permitted to make more than one selection and FCEVs were not included in the choices. Although such surveys have value in indicating trends, they do not reflect present realities. Hybrid vehicles, for instance, still account for less than 3 percent of annual U.S. new-car sales more than 12 years after their introduction in the market. J.D. Power and Associates found in its most recent "green" vehicles study that its research into consumer attitudes over the years shows that "while most consumers say they want to create a smaller personal carbon footprint . . . this consideration carries relatively low weight in the vehicle-purchase decision" (Humphries et al., 2010, p. 10).

Reasons for the strong preference for continued use of gasoline-powered vehicles appear to be based strongly on up-front cost—they are demonstrably less costly to purchase than alternatively fueled vehicles. The cost efficiencies realized by the tens of millions of internal combustion engines produced each year make petroleum-fueled cars and trucks far less expensive to purchase than any of the new crop of alternatively fueled/powered LDVs.

Convenience, especially the ready availability of fuel, is the second most-stated reason for preferring petroleum. The United States has a widespread gasoline service station network that serves even the smallest communities, and gasoline prices in the United States remain among the lowest in the world. Both factors make it incredibly convenient for consumers to continue purchasing and using gasoline-fueled vehicles. Perceived reliability of ICEVs versus alternative vehicles is another key factor, with some researchers finding that consumers believe conventional ICEVs are far more reliable than alternative vehicles (Synovate, 2011).

4.6 HOW CONSUMERS VALUE FUEL ECONOMY

Many consumers responding to attitudinal surveys say that they place fuel economy at or near the top of the list of factors they will consider when buying their next vehicle. But when it comes to applying potential fuel economy savings to the purchase decision, most research has shown that consumers just do not do it. So even though a case can be made for long-term fuel and maintenance savings making some AFVs less costly to own than gasoline vehicles over a period of years, a tendency by consumers to ignore such savings potential would make it more difficult for manufacturers and policy makers to persuade consumers to consider alternative fuels and vehicles with higher prices than conventional ICEVs. Researchers at the University of California, Davis, Institute for Transportation Studies, for instance, have found that consideration of a payback period for higher-priced AFVs "is not part of the vehicle purchase decision-making even in the most financially skilled households" (Turrentine and Kurani, 2007, p. 1220).

This tendency of consumers to fail to modify the up-front acquisition cost of AFVs by the long-term value of reduced fuel and other ownership costs (maintenance, repairs, and insurance chief among them) can be explained by applying behavioral economics' principle of loss or risk aversion. In general, increasing a vehicle's fuel economy through improved technology requires paying a higher initial cost. Future fuel savings, however, are uncertain due to the unpredictability of future fuel prices, the fact that the fuel economy consumers will achieve in actual use will differ from the government's ratings, and potential variations in vehicle use, lifetime, and other factors. Given the uncertainty in future fuel savings it is reasonable for a consumer to be reluctant to pay more for higher fuel economy. One of the most well established findings of behavioral economics is that when faced with a risky bet, typical consumers count potential losses approximately twice as much as potential gains and exaggerate the probability of loss. This approach can result in an undervaluing of future fuel savings by half or more relative to what would otherwise be expected (Greene, 2010a). Other possible explanations have been proposed, including shortsightedness and the lack of information or the necessary skills to estimate future energy savings. There is not an established consensus on this subject, however, and the published literature contains evidence to support both views—that consumers accurately value and that they undervalue future fuel savings (Greene, 2010b). Anderson et al. (2011) found that consumers typically take no position and merely consider future fuel prices to be the same as today's because they cannot accurately predict. Because the evidence for undervaluing appears to be stronger, the analyses and modeling in Chapter 5 assume that consumers behave as though they required a simple 3-year payback for an expenditure on higher fuel economy.

Overall, there is little doubt that a significant portion of consumers are interested in fuel efficiency. A variety of recent studies and surveys have shown that fuel economy is a top concern of 60 to 80 percent of prospective auto buyers (Consumer Reports, 2011a). Just how important, however, seems to depend on what it will cost the consumer to achieve a higher degree of efficiency. J.D. Power and Associates consumer research over the years has shown that "many may consider it, but when the time comes to put their money where their mouth is, very few follow up," the research firm's senior manager of global powertrain forecasting, Michael Omatoso, said in an interview (personal communication, M. Omatoso, Troy, Michigan, September30 2011). There have been a number of studies that include attempts to discern the premium consumers are willing to pay for AFVs, and they find it most typically is in the range of $1,600 to $2,000 (Boston Consulting Group, 2011; Deloitte Touche Tohmatsu Ltd. Global Manufacturing Industry Group, 2011). But as more AFVs come into the marketplace, the issue seems to remain a fertile field for future research.

4.7 INTEREST IN AFVs LIMITED

There is interest in AFVs, but it is limited by a number of factors including a general unwillingness to abandon a fuel and powertrain combination that has shown itself to be quite effective in providing for consumers' transportation needs over the decades, even if that effectiveness is not accompanied by the levels of environmental cleanliness necessary to achieve the nation's present goals. In a 2010 survey of consumer adoption literature, researchers at the University of Wisconsin found broad agreement that there is considerable interest in AFVs if performance characteristics remain comparable to those of ICEVs (Guo et al., 2010). Now that there are some of these vehicles in the marketplace (most notably conventional hybrids, although at this writing there is one compressed natural gas passenger car, two BEVs, and one PHEV in the market, pricing for several more BEVs and PHEVs has been announced, and there are several test programs utilizing fuel-cell electric vehicles), it has become clear that initially these vehicles will cost more and in most cases provide a reduced user experience—based on range and fueling convenience issues—than conventional ICEVs. As a result, more recent studies have predicted relatively slow and low adoption rates for AFVs, typically—in the aggregate—below 20 percent of the U.S. market by 2025 (Humphries et al., 2010).

4.8 BARRIERS

Although cost and convenience are the most-often cited reasons for anticipated low adoption rates, they are but are two of several significant barriers to AFV adoption cited when consumers are asked to list, or to pick from a prepared list, those things that most concern them about alternatively fueled vehicles (Table 4.3). All of these concerns must be addressed via public policy and/or manufacturers' marketing efforts if the best fleet mixes necessary to meet the goals set out in the committee's statement of task are determined—as indicated by the modeling results in Chapter 5—to be those requiring large numbers of AFVs. Such efforts will be needed to help overcome objections to vehicles that at least initially could offer less performance, range, utility, and fueling convenience and will cost consumers more to purchase than conventional ICEVs with advanced-technology gasoline powertrains that will not have the higher initial costs.

TABLE 4.3 Principal Barriers to Adoption of AFVs

Reason That Could Influence Purchase Decision of an Alternative-fuel Vehicle	Percent Respondents in Each Study Citing Reason as a Concern			
	Auto Techcast	Gauging Interest[a]	Green Auto[b]	Mineta[c]
Cost vs. comparable conventional vehicle	NA	74	35	53
Fuel availability	NA	75	32	55[c]
Fuel cost	30	NA	17	46
Payback period	46	49	18	NA
Performance		49	16	
Range (BEVs)	43	75	12	49
Refueling/Recharging time/convenience	38	NA	NA	55[c]
Reliability	26	57	17	NA[d]
Size/Seating capacity	17	33	NA	NA

[a] Gauging Interest responses are from U.S. participants only.

[b] Green Auto responses are only from consumers who said they would not purchase an AFV.

[c] Mineta survey, by Nixon and Saphores, combines fuel availability and refueling time.

[d] NA = Not asked.

SOURCE: Data from Harris (2011); Ernst & Young (2010); J.D. Power (2011); Nixon and Saphores (2011).

In its recent "Drive Green" study (Humphries et al., 2010), J.D. Power and Associates set out to determine the perceived drawbacks to specific types of AFVs. Researchers found that while there are differences in degree and in rankings, the top reasons in all cases (HEVs, clean diesel, PHEVs, and BEVs [fuel-cell electric vehicles were not asked about]) were the so-called initial cost premium consumers attached to most AFVs and the perceived long-term cost of ownership (exclusive of the purchase price premium), which some respondents believed to be higher for an AFV than for a conventional ICEV.

In the case of BEVs and PHEVs, concerns about driving range on a single battery charge also ranked high. This should not be an issue with PHEVs because they can be driven using their gasoline engines or engine-generators and are not solely dependent on batteries, showing continuing consumer confusion about the differences among the advanced powertrain technologies.

Range also could be an issue with AFVs using compressed natural gas. The only factory-built model currently in the market is the Honda Civic Natural Gas. Its design retrofits the CNG fuel storage and delivery system into a vehicle designed for petroleum-based gasoline. The pressurized tanks needed for the CNG occupy much of the vehicle's trunk area and even then hold only the usable equivalent of 7.5 gasoline gallons. While the CNG Civic attains almost the same EPA combined city-highway fuel economy rating as the gasoline model (32 mpg vs. 33 mpg), its smaller-capacity fuel tank limits its range to about 240 miles versus the gasoline Civic's estimated range of 430 miles. However future CNGV are likely to be designed from the ground up and could better house larger fuel tanks, thus enabling them to deliver improved range.

The move to more efficient, lower-emission LDVs almost certainly means that cars and trucks, regardless of the fuel source or powertrains, will have to be lighter than they are today. Present and proposed federal Corporate Average Fuel Economy (CAFE) policy is devised to enable larger vehicles to continue to meet the standards and does not necessarily lead to downsizing of the fleet to go along with the lightweighting. But downsizing has occurred, principally for economic reasons stemming from the recession of 2008-2010 and subsequent slow economic recovery and prolonged period of high unemployment. While that raises concern among those who find that consumers today do not want to give up size for efficiency, it might not be as big an issue in the future. Sales of larger vehicles could begin climbing as the economy improves in the future. But as younger consumers who today are in the used-car market or still are too young to be car purchasers begin replacing Baby Boomers and Gen-Xers in the new-car market, there may be a generational shift toward a preference for smaller cars.

In the past decade, according to sales data from online automotive information provider Edmunds.com (see Figure 4.1), the U.S. market share for small cars—a category including compact and subcompact cars, vans, SUVs, and compact pickup trucks—has increased by 53 percent from 20.3 percent in 2002 to 31.1 percent in 2011 (Edmunds.com, 2011); at the same time, the average price of a gallon of regular-grade unleaded gasoline has increased by 88 percent when adjusted for inflation.

For decades, sales activity for small cars and trucks seemed to correspond closely to fluctuations in retail gasoline prices. But as Hughes et al. (2008) found in their study of gasoline price inelasticity, driver behavior triggered by increases in gasoline prices has changed considerably in the past decade. Price run-ups may no longer lead as rapidly as in the past to the behavior changes once commonly associated with periods of unusually high gas prices—driving less and buying smaller and more efficient vehicles are two examples. In addition, fleet fuel efficiency has increased in recent years, dampening the impact of rising gasoline prices. Small vehicles' share of the LDV market keeps gradually increasing, but this could be a sign of increased general market acceptance as well as a reaction to several years of a weak national economy. It also could be related to the downsizing of aging Baby Boomers' households and transportation needs.

Both Edmunds.com and auto industry consulting firm AutoPacific, Inc. track consumer consideration of compact and subcompact vehicles. (Edmunds derives shopper consideration rates from details gleaned from consumer searches on its website—repeated, lengthy, and detailed research into a specific model equates to "consideration" of that specific vehicle type versus casual browsing; AutoPacific uses a bimonthly internal online consumer intent survey that asks approximately 1,000 respondents what types of LDVs they are considering for their next purchase.) Each recently compared small-car consideration rates to fluctuations in gasoline prices. Both indicate that while consideration rose sharply and in lockstep with price run-ups in the first half of 2007 and the last half of 2008, consumers may not be increasing their consideration of small cars at the same pace in the most recent series of gasoline price hikes, which began in September 2010 (Figure 4.2). That data and the previously mentioned small-vehicle sales versus fuel price data (see Figure 4.1) appear to further validate the results of Hughes et al. (2008), but also could mean that while fuel price still matters, price increases have to be very large in order to elicit significant movement toward smaller, more efficient vehicles. This would mean that policies based on only modest increases in fuel taxes or other fuel-efficiency related fees would be less likely to succeed than policies such as CAFE standards, or

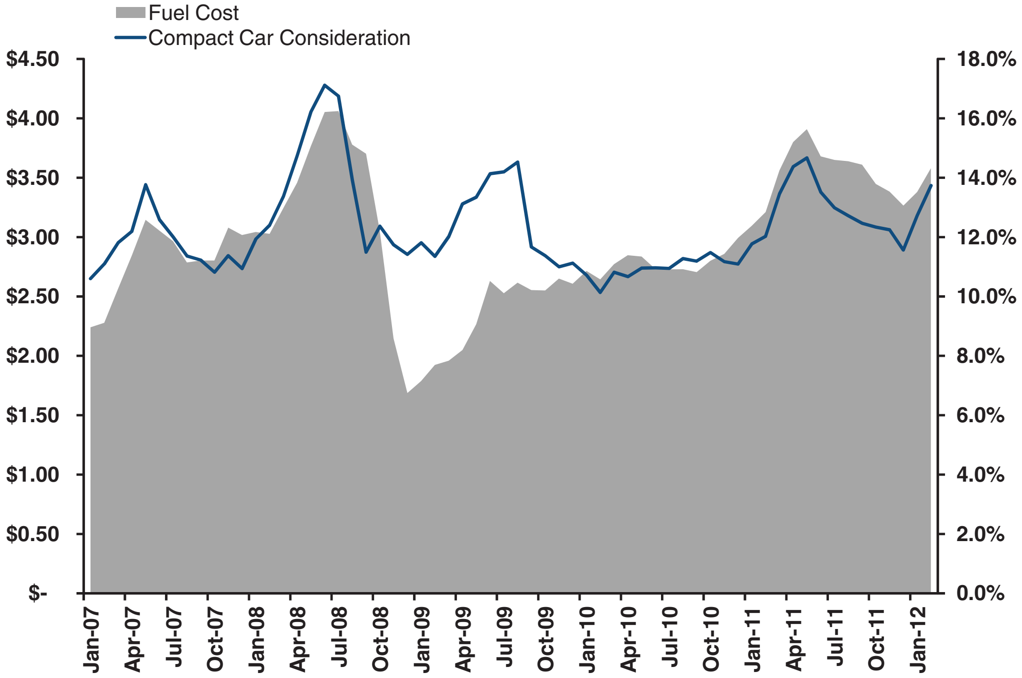

FIGURE 4.2 Compact car consideration and fuel cost.
NOTE: "Normal" consideration level is in the range of 10 to 12 percent. Consideration spike in the period of February to September in 2009 corresponds to the U.S. "Cash for Clunkers" economic stimulus program in which consumers received funds to apply to the purchase of new, more efficient vehicles in return for junking older, less-efficient models.
SOURCE: Data provied by Edmunds.com Data Center; chart prepared for this report by Edmunds.com.

fee systems aimed at making the use of inefficient and/or high-emissions vehicles prohibitively expensive.

"People remember the gas (price) spike in 2008 and how a lot of people panicked and downsized their vehicles, only to see (gas) prices drop. So now they are taking a wait-and-see approach," said market researcher George Peterson, president of AutoPacific (personal communication with G. Peterson, Troy, Michigan, August 25, 2011). He said the so-called tipping point at which consumers say they would change their new-vehicle buying goals and shop for more efficient vehicles has steadily increased and now is about $5.50 a gallon, up from $3 a gallon just a decade ago. Undoubtedly, the tipping point will continue to increase with economic recovery and improving fuel efficiency for ICEVs.

4.9 PEER INFLUENCE CRITICAL

Advanced alternative fuels and powertrains are still rare and consumers have had very little real-world experience with them. Thus there's little solid information available to help determine what consumers will accept in the way of alternatives to gasoline- and diesel-fueled vehicles.

In fact, there is some concern that this lack of knowledge has led to confusion in the marketplace about the characteristics, values, and drawbacks of the various types of AFVs and has caused some degree of consumer paralysis (Synovate, 2011). Researchers on both sides of the country, however, have found that word of mouth can be a powerfully influential tool, pointing to the potential value both of public demonstration and deployment programs and of public information campaigns. Axsen and Kurani argue that the mere presence of greater numbers of AFVs on the nation's roads will increase both public awareness and public acceptance as the real-world experiences of many drivers are communicated to friends, neighbors, family members, and co-workers (Axsen, 2010; Axsen and Kurani, 2011). Zhang et al. (2011) found that positive word of mouth increases the perceived value of AFVs and leads to a higher willingness by consumers to pay a premium for them. Such studies show that getting AFVs into the market, even in small numbers, would generate word-of-mouth reports that could help put to rest (although there is also the possibility that some will reinforce) the negative concerns about barriers that appear to be limiting AFV acceptance at this point. Price disparity, however, still can be a strong disincentive, as has been shown by the slow market penetration of conventional hybrid vehicles, which still account for less than 3 percent of the U.S. LDV market more than a decade after introduction. Consumers do not have many negative attitudes about hybrids any longer. But because most HEVs still have a price premium when compared to comparably sized and equipped ICEVs, sales have risen and fallen with gasoline prices in recent years but overall have leveled off in the range of 2.5 to 3 percent.

It should be pointed out again that these early positive reports are coming from a unique and generally accepting group of AFV purchasers, the so-called early adopters whose interest in and desire to possess advanced technologies invariably make them prone to acceptance. Engineers at Nissan Motor Company, for example, told the committee that early Nissan Leaf owners were adapting to the Leaf's characteristics in ways that mainstream buyers might not. For example, the heating system on a BEV is a significant drain on the battery charge, reducing range when in use. As a result, many early Leaf owners have developed the technique of using the car's seat heaters—which draw much less charge from the battery—rather than the cabin heater. It is uncertain whether a potential mainstream buyer would see that as a plus or a minus.

4.10 INFRASTRUCTURE AVAILABILITY

The availability of fuel, including battery-charging facilities for BEVs, is also a major issue affecting consumer willingness to acquire AFVs. There are so few of the vehicles and so little infrastructure available at present that it is not possible to determine the necessary balance. One exception is E85 fuel (which is a blend of 85 percent ethanol and 15 percent gasoline) and the "flex-fuel" vehicles built to use either gasoline or E85. There often is no financial incentive for the owner of a flex-fuel vehicle to purchase E85. While a gallon of E85 may cost less than a gallon of gasoline, it delivers significantly fewer miles.

Earlier studies of consumer adoption in Canada and New Zealand of flex-fuel, or dual-fuel, vehicles using CNG as the alternate fuel found that the presence of refueling infrastructure was a significant factor in consumers' decisions to acquire such vehicles. Greene (1990) concluded after reviewing a Canadian government survey of consumers in the provinces of Quebec, Ontario, and British Columbia that a "substantial refueling network is a pre-condition for the markets accepting alternative fuel vehicles and . . . essential if dual- or flexible-fuel vehicles are to use the new fuel a significant fraction of the time." In their study of buyers of CNG vehicle conversions in New Zealand in the 1980s, Kurani and Sperling (1993) found that successful achievement of the government's goal of pushing 150,000 converted vehicles into the market between 1979 and 1986 (that goal was not met; the total number of conversions by 1986 was 110,000) depended in large part on two types of government subsidies: those that helped consumers defray or earn back the cost of acquiring the converted vehicles, and those that helped underwrite new CNG fueling stations so that consumers would perceive that a fueling infrastructure was being installed and that they would have access to the fuel. The CNG conversion program ended—dropping from 2,400 a month in 1984 to 150 a month in 1987—following a 1985 change of administrations that saw significant curtailment of government subsidies for the program.

From these studies and from consumers' stated concerns in the more recent studies cited earlier in this chapter, it is clear that policies aimed at promoting increased use of AFVs will have to address adequate provision of infrastructure.

4.11 IMPLICATIONS

To painlessly achieve any necessary transition to alternative light-duty cars and trucks, the new-generation vehicles intended to replace petroleum-burning LDVs will have to provide utility, value, creature comforts, style, performance, and levels of convenience in fueling and repair and maintenance service that closely replicate those of the liquid-fueled vehicles being phased out. They are going to have to fulfill consumers' needs and desires, or consumers will have to be presented with disincentives to continued purchase of conventional ICEVs or offered various incentives to make up for the things they perceive they would lose in a switch to an alternative vehicle or fuel. Most people do not want to pay more for a green vehicle, and of those who are willing, most would expect fuel and other savings to recoup the additional purchase expense over their period of ownership. Boston Consulting Group recently found in a survey of 6,593 consumers in the United States, Europe, and China that 40 percent of U.S. and European car buyers say they would be willing to pay up to $4,000 more for an AFV but would expect full "payback" over the first 3 years of ownership (Boston Consulting Group, 2011). Only 6 percent of U.S. respondents said they would be willing to pay a premium—the average was $4,600—without expecting to earn back the money during their full ownership period (Boston Consulting Group, 2011).

So although consumers overwhelmingly say that they want fuel efficiency and energy security, they have not demonstrated a willingness to pay much extra for it or to accept inconvenience in order to attain it. Vehicle purchase price, the long-term cost of ownership, the time it takes to refuel, the availability and cost of fuels, and the perceived need to downsize and to surrender performance attributes such as speedy acceleration and cargo and towing capacity all are cited in various studies as reasons people are not interested in AFVs. Some of this is due to lack of information, and studies such as those conducted by Axsen and Kurani (2011) and Zhang et al. (2011) have shown that word of mouth and demonstrated use by neighbors, friends, and relatives all have a positive impact on consumers' willingness to consider AFVs. That, of course, requires getting the vehicles into people's garages and onto the roads.

Some of these barriers, of course, are likely to change over time. As additional advanced-technology vehicles are placed into service, public familiarity with and knowledge of their advantages, and will improve, perhaps mitigating perceived disadvantages. AFVs also will develop a track record for resale value—a key component in determining overall cost of ownership and one that is missing now because few of the vehicles have been in the market long enough to develop a resale value history. Early estimates published by the manufacturers and a few ratings companies and analysts show that BEVs and PHEVs are thought to have lower lease residual values, an indicator of marketplace resale value. Pike Research analyst David Hurst estimated in 2011 that both the Nissan Leaf and the Chevrolet Volt would have residuals of around of 42 percent at 3 years—lower than either the popular Toyota Prius, which has a 60 percent residual value at 3 years, or corresponding conventional ICEVs such as the Nissan Versa (a Leaf counterpart) or the Chevrolet Cruze (a Chevrolet Volt counterpart), both at 52 percent (Hurst, 2011).

The relatively rapid rate of performance improvement and cost reduction that is characteristic of some new technologies can both help and harm rapid adoption of AFVs, fostering a larger market by lessening both cost and convenience barriers. Rising production volumes for biofuels could bring down their costs and make them more widely available, similarly addressing two barriers in ways that can accelerate expanding demand. Improved batteries and battery-charging rates could help reduce or even eliminate BEV range anxiety, fostering a larger market by lessening both cost and convenience barriers. Rising production volumes for biofuels could bring down their costs and make them more widely available, similarly addressing two barriers in ways that can accelerate expanding demand. Improvements in materials and engineering could make it possible to produce AFVs that are competitive with gasoline vehicles with respect to cargo capacity, towing ability, and other performance characteristics, and without the cost premiums that would inhibit widespread adoption. Conversely, rapid rates of technology advancements could inhibit diffusion beyond an early-adopter segment. Such progress would hasten the obsolescence of earlier generations of an advanced AFV technology and also suppress residual values. For example, if ongoing improvements in battery technology, such as steadily decreasing costs and rising performance, reduce the purchase price of a newer BEV relative to older BEVs still operating within their battery life expectancies (see Chapter 2), then early AFV models could depreciate more rapidly than is typical in the car market. This could lead to expectation among consumers of additional advances in the future, and a corresponding uncertainty about how well new generations of BEVs would hold their value if additional advances do indeed occur. This uncertainty could inhibit purchases by consumers concerned about resale value or could result in unfavorable lease terms.

However, because of the time it takes for automakers to bring new technologies into their fleets and for the national LDV fleet to turn over, these barrier modifications would have to be in place by or before 2030 to have a great impact on the fleet in 2050.

Absent a national emergency that requires consumers to abandon the gasoline or diesel ICEV, achieving the volumes needed to realize sufficient consumer acceptance in the early years of a planned transition to AFVs is unlikely without significant government policy intervention.

The simulations described in Chapter 5 suggest that the types of AFVs that might be needed to achieve the desired levels of petroleum and GHG reduction are those that initially will carry a large price premium because of their technology content. Once advanced vehicle technologies have become widely diffused, the vehicles in which they are incorporated will become much closer in cost to the advanced "conventional" vehicles that then would be available. In fact, the committee's midrange case shows that both BEVs and FCEVs could cost less than advanced ICEVs by 2050. (See Figure 2.8 in Chapter 2.) In addition, the superior energy efficiency of those alternative vehicles would return more than enough benefit to consumers, in terms of reduced fuel consumption, to offset any cost premium that did exist. The trick will be to persuasively convey this information to consumers.

Accomplishing this is likely to require increased understanding of consumers' attitudes about issues of sustainability, climate change, and environment and of how to motivate consumers in these arenas. The President's Council of Advisors on Science and Technology has recently recommended that the Department of Energy incorporate societal research in its programs to gain an understanding of how energy programs succeed in the market (PCAST, 2010).

Broadening such research to include a focus on understanding consumer attitudes, expectations, and past behaviors relative to alternative automotive and fuel choices as well as to other technologies introduced to increase fuel efficiency and reduce emissions would seem essential to successful achievement of the petroleum use and GHG reduction goals set out for the 2030 and 2050 time periods in the committee's statement of task.

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5

Modeling the Transition to Alternative Vehicles and Fuels

5.1 INTRODUCTION

Achieving the goals of reducing light-duty vehicle (LDV) petroleum use and greenhouse gas (GHG) emissions by 80 percent by 2050 and petroleum use by 50 percent by 2030 is likely to require a transition from internal combustion engines powered by fossil petroleum to alternative fuels or vehicles or both. There is also potential for significant technological advancement both in the LDV fleet and in the fuel and fueling infrastructure that will power vehicles over the next 40 years. Which of these technologies will actually enter the market depends on a range of factors, including the extent of progress in the different vehicle and fuel technologies, market conditions in gasoline and other fuels markets that will affect cost and competiveness, consumer preferences over vehicle and fuel characteristics, and government policies toward this sector. Government policies are likely to be particularly important because the benefits of both petroleum and greenhouse gas reductions accrue to the public as a whole, and so market forces alone cannot be relied on to provide sufficient reductions.[1]

Two different models were used by the committee to assess the potential and opportunities for achieving the goals of this study. The first was the VISION model developed by Argonne National Laboratory (Singh et al., 2003). This spreadsheet model was an ideal starting point for the committee's analysis because it has been widely used in the past for light-duty vehicle (LDV) sector forecasts of energy use and GHG emissions. All inputs must be specified, including future rates of penetration of vehicle and fuel types and the costs of each. VISION does not, however, attempt to estimate how markets will react to alternative vehicles and fuels or to the policies that may be needed to successfully introduce them.

The second model, the Light-duty Alternative Vehicle Energy Transitions (LAVE-Trans) model, incorporates market decision making and reflects the most significant economic barriers to the adoption of new vehicles and fuels. It therefore allows for assessment of policies and possible transition paths to attain the goals. Penetration rates of different vehicle and fuel types are determined in this model in response to price, costs, and vehicle fueling characteristics; they are not simply assumed as they are in VISION. Moreover, LAVE-Trans includes a consistent and comprehensive assessment of the benefits and costs of different policy and technology pathways over time.

It is important to emphasize the nature and extent of the uncertainties that lie behind all of the analyses in this chapter. First, the analysis uses estimated improvements to fuel efficiency and fuel carbon content, and the associated costs, for vehicles up to the 2050 model year as provided by expert members of this committee, evidence from the literature, and consultation with experts outside the committee. (Detailed descriptions can be found in Chapters 2 and 3.) Both models use the same GHG emissions, fuel economy, and vehicle cost estimates. These estimates by necessity reflect numerous assumptions, most of which are highly uncertain, particularly when such forecasts are made far into the future. One way the committee represents this uncertainty is to include both "midrange" and "optimistic" estimates for important variables such as vehicle fuel efficiency and fuel carbon intensities. However, it is difficult to reflect the full range of uncertainty. Thus, a "pessimistic" case is not included here for vehicles in which either technology does not progress very rapidly or costs do not come down over time and with volume as expected.

There is, in addition, uncertainty in the assumptions about consumer preferences for different vehicle characteristics,

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[1] Both petroleum use reduction and GHG emissions reduction are types of public goods in that once they are reduced, all members of society benefit through greater security and reduced risk of global climate change. No one is excluded from these benefits. The private sector will tend to underprovide such goods because private individuals must pay the costs of reductions but do not get all of the benefits—the benefits are shared by all. When there are public goods, then, government action may be essential for attaining amounts of the public goods that are economically efficient for society (Boardman et al., 2011).

including range and limited fuel availability for alternatives such as hydrogen fuel cell vehicles.[2] A sensitivity analysis illustrating uncertainties about the market's response to alternative vehicles and fuels is described in Section 5.7. There is also controversy about the magnitude of the social cost of GHG emissions and the social cost of the United States' reliance on oil and petroleum-based gasoline. The estimates used in this report are drawn from the most recent literature but do not reflect the full range of uncertainty. Finally, it is extremely difficult to model all of the feedback effects that will inevitably result over time as technology development and markets interact.

Despite the inherent uncertainties in attempting to forecast four decades into the future, the committee's modeling effort here uses the best available evidence and information and makes plausible assumptions where sound data are missing. Analysis of the results from the two models then provides useful insights about what various vehicles and fuel combinations can achieve, the nature of the processes by which changes will occur, and the general magnitude of potential costs and benefits of different policy options.

5.2 MODELING APPROACH AND TOOLS

5.2.1 VISION Model

VISION is designed to extend the transportation sector-specific component of the National Energy Modeling System (NEMS) used by the Energy Information Administration (EIA). It provides longer-term forecasts of energy use and GHG emissions than does NEMS. While not as detailed or comprehensive as the NEMS model, VISION provides greater flexibility to analyze a series of projected usage scenarios over a much longer timeframe. It has been used extensively in the literature.

For the purposes of this study, VISION has been modified in a number of ways. The most up-to-date assumptions from the committee about vehicle efficiencies, fuel availability, and the GHG emissions impacts of using those fuels have been included. It is assumed that new-technology vehicle sales ramp up slowly and that new sales for a particular vehicle type never increase by more than about 5 percent of total new LDV sales in a given year. In addition, only one plug-in hybrid electric vehicle (PHEV), a PHEV-30 with a real-world all-electric driving range of 25 miles, is included. It is assumed that because of their limited range, battery electric vehicles are to be driven 1/3 fewer miles per year than other vehicles (Vyas et al., 2009) and that any decrease in miles driven by electric vehicles will be offset by increased mileage from other vehicles. Total new car sales and annual vehicle miles traveled (VMT) are assumed to be the same as in the projections from the *Annual Energy Outlook 2011* (AEO; EIA, 2011a), and there is no assumption of a "rebound effect"[3] if the cost of driving a mile declines. Adjustments to VMT can be included separately in any VISION run assessment.[4] Finally, GHG estimates from biofuels include both emissions from production and from indirect land-use changes (see Chapter 3).

The committee uses the VISION model to explore how a focus on specific technologies or alternative vehicle and fuel types has the potential to reduce oil use and GHG emissions to achieve the study goals. The committee then turns to the LAVE-Trans model to shed light on how policies might be used to achieve the needed transitions.

5.2.2 LAVE-Trans Model

The Light-duty Alternative Vehicle Energy Transitions (LAVE-Trans) model uses a nested, multinomial logit model[5] of consumer demand to predict changes in the efficiency of vehicles and fuels over time, including a possible transition to alternatively fueled vehicles. Any transition to these advanced vehicles faces a number of barriers, including high costs due to the lack of scale economies and lack of learning, consumer uncertainty about safety or performance, and the lack of an energy supply infrastructure. Each of these barriers has been incorporated into the LAVE-Trans model so that the costs of overcoming them and, alternatively, the benefits of policies needed to do so can be measured (subject to the limits of current knowledge).

The model incorporates an array of factors that affect and are derived from consumer behavior, including the rebound effect; "range anxiety" and perceived loss of utility, particularly as it pertains to the availability of a fueling infrastructure; aversion to new technology and its reciprocal effect, early adoption; and the significant discounting of future fuel benefits over the lifetime of the vehicle. Nine variables influence the market shares of the alternative advanced technologies:

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[2] Thanks to recent research, such issues are better understood than they were a decade ago (e.g., UCD, 2011; Bastani et al., 2012), yet much remains to be learned.

[3] Improvements in the efficiency of energy consumption will result in an effective reduction in the price of energy services, leading to an increase of consumption that partially offsets the impact of the efficiency gain in fuel use. This is known as the "rebound effect."

[4] If a 5 percent reduction in vehicle miles traveled is plausible under certain policies, then the estimates of GHG emissions and oil use can be reduced by 5 percent.

[5] A multinomial logit model is a standard model often used to represent consumer choice where there is a finite set of discrete options. The probability of choosing among the set of available options is governed by representative parameters for a particular class of consumer. A nested model refers to multiple layers of choice (see Daly and Zachary, 1979; McFadden, 1978; Williams, 1977). For example, the first level of choice in the LAVE-Trans model is between choosing whether or not to buy an LDV. If a consumer chooses to buy an LDV, the next level of choice is between purchasing a passenger car or a light truck. Then, within a particular class of vehicle there are multiple options, such as whether to purchase an ICEV, FCEV, or BEV. Further description of the LAVE-Trans nested multinominal logit model can be found in Section H.2 in Appendix H.

1. Retail price equivalent (RPE),
2. Energy cost per kilometer,
3. Range (kilometers between refuel/recharge events),
4. Maintenance cost (annual),
5. Fuel availability,
6. Range limitation for battery electric vehicles (BEVs),
7. Public recharging availability,
8. Risk aversion (innovator versus majority), and
9. Diversity of make and model options available.

It also includes policy options that affect consumer choices, including new-vehicle rebates, incentivized infrastructure development, and fuel-specific taxation. Although both the LAVE-Trans and VISION models use the same committee-developed technology and cost assumption for different vehicles and fuels over time, the LAVE-Trans model represents a significant improvement over the VISION model in several ways. First, because it includes consumer behavior in the vehicle market, it is able to predict the shares of different vehicles that enter the market in response to policy and market changes, whereas VISION must assume these shares over time. Thus, LAVE-Trans is much better able to assess the types of policies that may be necessary to achieve the goals addressed in the present study. Second, LAVE-Trans can be used to assess the full range of benefits and costs of different policies. The committee's approach to measuring benefits and costs is discussed more fully below.

5.3 RESULTS FROM RUNS OF VISION MODEL

Forecasts of the penetration rates of different types of vehicles using the VISION model must be compared to some alternative outcome in which there are no further policy actions and limited technological advances. In this analysis, two such cases are presented. One is the business as usual (BAU) case. It closely follows the AEO 2011 reference case projection to 2035 and from there is extrapolated to 2050. In this case, NHTSA CAFE and EPA GHG emission joint standards for LDVs are set out to 2016, with fuel economy continuing to increase to 2020 per the Energy Independence and Security Act of 2007. Renewable fuel production increases in response to RFS2 (the amended Renewable Fuel Standard), but it is assumed that financial and technological hurdles facing advanced biofuel projects will delay compliance. The other case is the Committee Reference Case. It adds to the BAU case the CAFE rules that have been set through the 2025 model year, and the levels of advanced biofuels production required under RFS2 are assumed to be fully met by 2030 through the production of thermochemical cellulosic biofuel.

5.3.1 Baseline Cases

5.3.1.1 Business as Usual (BAU)

In the BAU case, new-vehicle sales increase to 22.2 million in 2050 from 10.8 million units in 2010 (a year in which sales were severely depressed due to the recession). Diesel, hybrid, and plug-in hybrid vehicles make modest gains in market share (Figure 5.1). The total stock of LDVs increases from about 220 million in 2010 to 365 million in 2050.

Fleet average on-road fuel economy improves from 20.9 miles per gallon gasoline equivalent (mpgge; equivalent to a consumption of 4.8 gge/100 mi) in 2005 to 34.7 mpgge (or 2.9 gge/100 mi) in 2050. This is consistent with the Energy Independence and Security Act of 2007, which requires a fleetwide fuel economy test value of at least 35.5 mpg in 2020 and includes modest improvements in vehicle efficiency thereafter. This is enough to offset most of the forecasted increase in vehicle travel from 2.7 trillion to 5.0 trillion miles. Energy use increases to 159 billion gallons gasoline equivalent (billion gge) from 130 billion gge. Com-

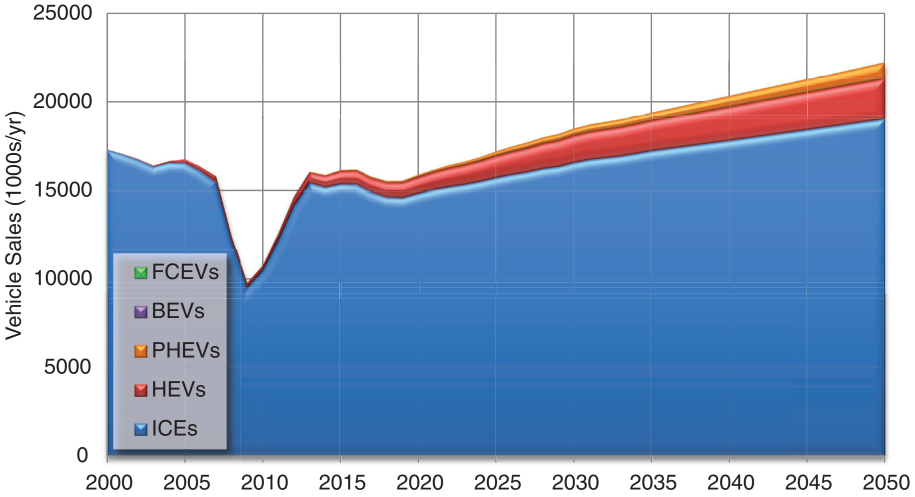


FIGURE 5.1 Vehicle sales by vehicle technology for the business as usual scenario.

pared to 2005 levels, petroleum use remains unchanged, the result of increased use of corn-based ethanol (to 12.0 billion gge/yr in 2050) and the addition of 8.9 billion gge/yr of cellulosic ethanol and 8.1 billion gallons of gasoline produced from coal. The net effect of increased overall energy use and the shift to a somewhat less carbon-intensive fuel mix is a 12 percent increase in 2050 GHG emissions.

Oil prices in this scenario are expected to gradually increase to $123/bbl by 2035 (in 2009$) according to AEO 2011, resulting in a pre-tax gasoline price of $3.16 in 2035. Gasoline prices are then extrapolated out to 2050 assuming the compound rate of growth modeled in AEO 2011 from 2030 to 2035, yielding a pre-tax price of $3.37. The current gasoline tax of $0.42/gal is assumed to remain the same (in constant dollars) out to 2050. Gasoline prices in this scenario are shown in Figure 5.2. The pre-tax fraction of these gasoline prices is assumed in all modeling scenarios.

5.3.1.2 Committee Reference Case

The committee further defined its own reference case to include all of the midrange assumptions it developed about vehicle efficiencies, fuel availability, and GHG emission rates up to 2025 (summarized in Chapters 2 and 3). This Committee Reference Case assumes that the 2025 fuel efficiency and emissions standards for LDVs will be met. The committee interprets the standards to require that new vehicles in 2025 must have on-road fuel economy averaging around 40 mpg (given a fleetwide CAFE rating of 49.6 mpg for new vehicles, the difference between on-road and test values, and the likely application of various credits under the CAFE program). See Box 5.1 for an explanation of on-road fuel economy compared to tested fuel economy ratings.

This case also assumes that the RFS2 goals will be met by 2030. As a result, corn ethanol sales rise to almost 10 billion gge/yr by 2015 and then remain at that level. Based on the analysis in Chapter 3, it is also assumed that all cellulosic biofuels will be thermochemically derived gasoline. The RFS2 requirements result in annual production of 13.2 billion gallons of such biofuels by 2030 and roughly constant levels thereafter.

Under the assumptions of the Committee Reference Case, the fuel economy (fuel consumption) of the stock of LDVs in use improves to 35.5 mpgge (2.8 gge/100 mi) in 2030 and to 41.6 mpgge (2.4 gge/100 mi) in 2050, up from 20.8 mpgge (4.8 gge/100 mi) in 2005 (Figure 5.3). This improvement is largely due to efficiency improvements in internal combustion engine vehicles (ICEVs) as well as increasing sales of hybrid electric vehicles (HEVs). Hybrids are more successful in this scenario compared to the BAU case, increasing their share of new-vehicle sales to 33 percent (7.3 million units) by 2050.

Greenhouse gas emissions are 30 percent below 2005 levels in 2030, at 1,057 million metric tons CO_2 equivalent ($MMTCO_2e$) per year, but rise again and are just 22 percent below in 2050 (1,121 $MMTCO_2e$/yr) as VMT continues to rise while the efficiency of the on-road fleet remains approximately constant (Figure 5.4). Petroleum use is 36 percent below the 2005 level in 2030 (1.91 billion bbl/yr) and 30 percent below in 2050 (2.09 billion bbl/yr), also rising with

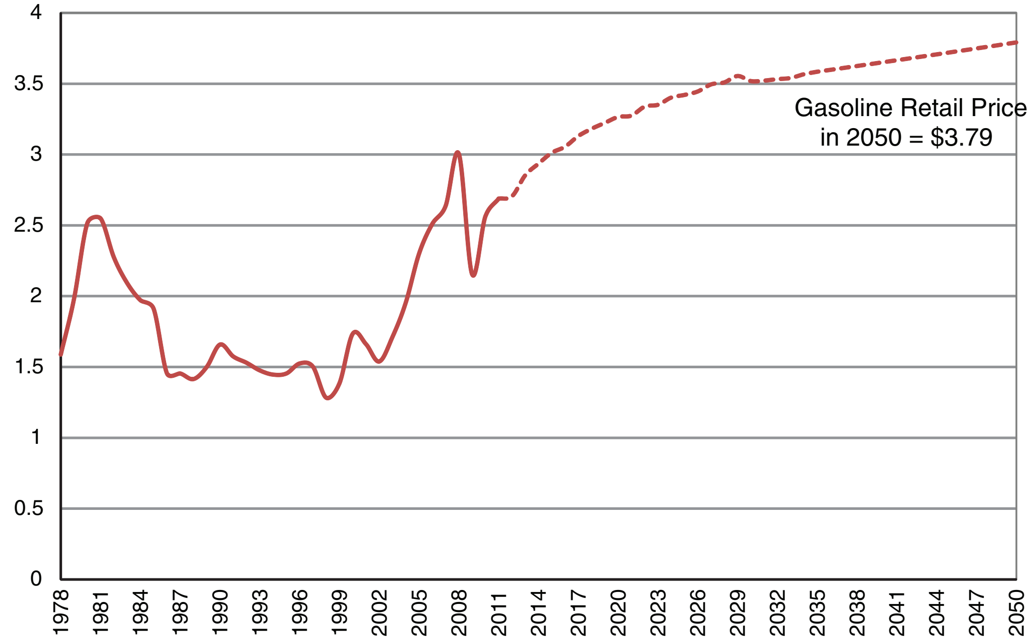


FIGURE 5.2 Retail gasoline fuel prices (1978-2050), including federal and state taxes. Projected values shown as dotted line. SOURCE: Data from *Annual Energy Review 2010* [1978-2010] (EIA, 2011b), *Annual Energy Outlook 2011* [2010-2035] (EIA, 2011a), and extrapolation by the committee using the compound annual growth rate for 2030-2035 (0.42%) [2035-2050].

BOX 5.1
The Distinction Between "As Tested" and "Actual In-Use" Fuel Consumption

A large difference exists between the fuel economy (miles per gallon, or mpg) figures used to certify compliance with fuel economy standards and those experienced by consumers who drive the vehicles on the road and purchase fuel for their vehicles. The numbers used to certify compliance with the Corporate Average Fuel Economy (CAFE) standards are based on two dynamometer tests. These test values are also the numbers discussed and presented in the tables and figures of this report. A different 5-cycle test procedure is used to compute the Environmental Protection Agency (EPA) "window-sticker" (label) fuel economy ratings that are used in automotive advertising, most car-buying guides, and car-shopping Websites. Neither procedure accurately reflects what any given individual will achieve in real-world driving. Motorists have different driving styles, experience different traffic conditions, and take trips of different lengths and frequencies. Realized fuel economy also varies with factors including climate, road surface conditions, hills, temperature, tire pressure, and wind resistance. The impacts of air conditioning, lighting, and other accessories on fuel consumption are not included in the two-cycle tests.

Both CAFE mpg and "window-sticker" mpg were based on the values determined via standardized city- and highway-cycle procedures that were codified by law in 1975. The divergence between test-cycle values and real-world experience was recognized and in 1985 the EPA revised calculation procedures for the window-sticker ratings in order to bring them more in line with the average performance motorists were reporting in real-world driving. From 1985 through 2007, the window sticker values averaged about 15 percent lower than the unadjusted values used for CAFE regulation. The label values were updated starting in model year 2008, and the update further increased the difference between CAFE and "window sticker" values by factoring in additional adjustments, so that the current window sticker values average about 20 percent lower than those used for regulation.

The results can be confusing. For example, the 2017-2025 CAFE rules envision a 49.6-mpg "fleet average new LDV fleet fuel economy" for the 2025 model year, but acknowledge that real-world fuel economy will be significantly lower—probably somewhere below 40 mpg. A further complication is that the "National Plan" (the joint rulemaking by NHTSA and EPA) regulates greenhouse gas (GHG) emissions in addition to fuel economy. Because some technologies for reducing LDV GHG emissions do not involve fuel economy, EPA now also reports a "mpg-equivalent" value representing the CAFE fuel economy that would be needed to achieve a similar degree of GHG emissions reduction. That type of number is the one given as the 54.5 mpg "equivalent" stated in many discussion of the 2025 target; it reflects special credits for various technologies that can help in achieving fleet average GHG emissions of 163 grams per mile by 2025.

The CAFE numbers represent a higher fuel economy than most consumers are likely to experience on the road. The estimates of actual fuel consumption and associated GHG emissions presented in this report, however, reflect a downward fuel economy adjustment for approximating real-world impacts. Although there is no universally agreed-upon method for converting test values to on-road values, the committee has determined that an appropriate estimate for analytic purposes can be obtained by adjusting the CAFE values downward by about 17 percent (i.e., multiplying by 0.833). That factor is used whenever the report discusses "average" on-road values.

VMT. Thus, the Committee Reference Case, which assumes current policies included in the AEO BAU case augmented by the proposed 2025 fuel economy and emissions standards and RFS2 compliance, does not come close to meeting the 2030 or 2050 goals.

5.3.2 VISION Cases

To explore possible paths to attain the goals addressed in this study, VISION was run for a range of cases. The predominant characteristic of these runs is to focus on a market dominated by a particular vehicle type and alternative fuel (e.g., electric vehicles and grid with reduced GHG emissions, or fuel cell vehicles and hydrogen generated with CCS). To assess the range of possibilities, the committee looked at runs that used the midrange vehicle efficiencies as well as at runs that used the optimistic efficiencies representing technological progress proceeding more rapidly than expected, as described in Chapter 2. From the fuels side, the committee considered both present methods of producing a fuel as well as fuel supply technologies with reduced GHG impacts as described in Chapter 3. Each of the possible fuel types is shown in Table 5.1. A brief description below of each of the scenarios modeled with VISION identifies the important assumptions and variation in those assumptions. Section H.1 in Appendix H provides further detail.

- *Emphasis on ICEV efficiency.* These runs continue the reference case's focus on LDV fuel efficiency improvements through the period to 2050. Shares of advanced ICEVs and HEVs increase to about 90 percent of new-vehicle sales by 2050. Two runs are included that differ only in their assumptions about the fuel efficiency improvements of vehicles over time. The first assumes the midrange assumptions for fuel efficiency for all technologies (Chapter 2, Table 2.12), and the second assumes optimistic fuel efficiency for ICEs and HEVs while maintaining midrange values for the small numbers of other types of vehicles in the fleet. It is assumed that the RFS2

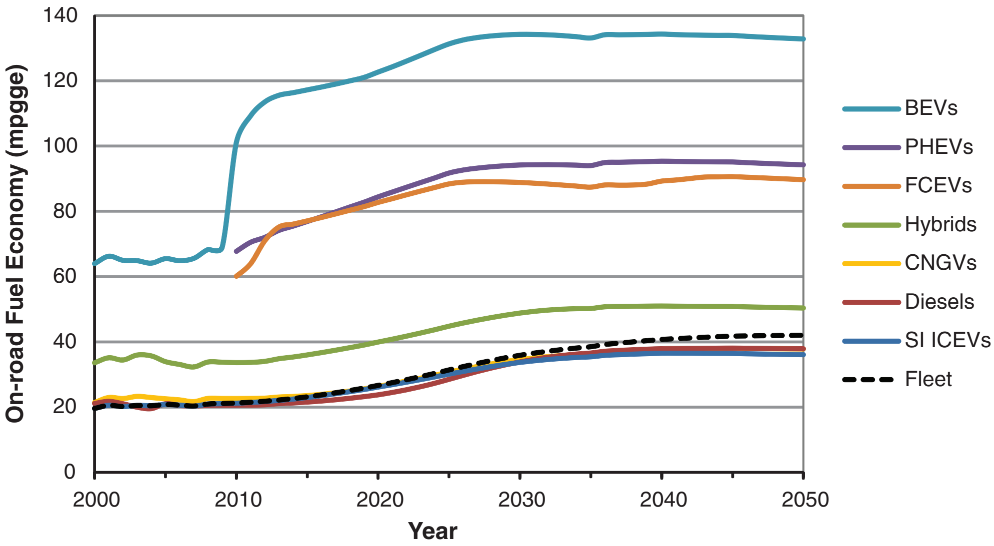


FIGURE 5.3 Average on-road fuel economy for the Reference case light-duty vehicle stock. In most cases, the average efficiency plateaus as the fleet gradually turns over to vehicles that meet the 2025 model year CAFE standard. There are small reductions over time with rising use of advanced technologies in trucks.

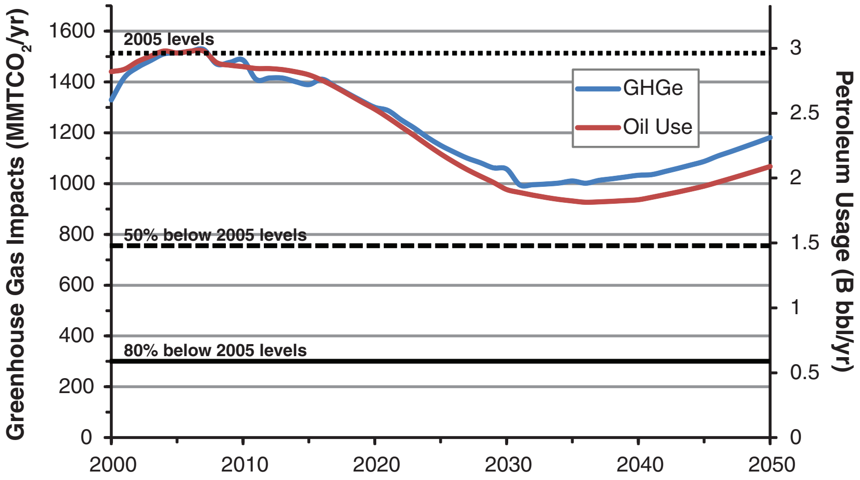


FIGURE 5.4 Petroleum use and greenhouse gas emissions for the Committee Reference Case.

requirements described in the Committee Reference Case, above, are still in place. These increased vehicle efficiency cases require much less liquid fuel over time and assume that gasoline is the fuel reduced.

- *Emphasis on ICEV efficiency and biofuels.* These two runs are similar to the case described above. The difference is that more biofuels are brought into the market after 2030, as described in Table 5.1. The modeling runs assume this additional biofuel, largely in the form of drop-in gasoline that displaces petroleum, and the only difference in the two runs is the assumption of vehicle fuel efficiency. The first run assumes all vehicles are at the midrange efficiency, and in it the share of petroleum-based gasoline as a liquid fuel falls to about 25 percent by 2050. The second run assumes optimistic fuel efficiency for ICEVs and HEVs. In this case, bio-based ethanol, bio-based gasoline, and a small amount of coal-to-liquid (CTL) and gas-to-liquid (GTL) fuels make up all liquid fuel, with almost no petroleum-based gasoline.
- *Emphasis on fuel cell vehicles.* This case comprises 4 different runs of VISION, to capture variation in both vehicle efficiency and fuel carbon content. In all of these runs, the share of fuel cell electric vehicles (FCEVs) increases to about 25 percent of new car sales by 2030 and then to 80 percent by 2050, modeled on the maximum practical deployment scenario from *Transition to Alternative Transportation*

TABLE 5.1 Description of Fuel Availabilities Considered in Modeling Light-Duty Vehicle Technology-Specific Scenarios

Fuel Type	Description (values reflect annual production in 2050)
AEO 2011	AEO 2011 projection extrapolated to 2050; 12.0 billion gge corn ethanol; 8.9 billion gge cellulosic ethanol; 8.1 billion gal CTL gasoline
Reference	RFS2 met by 2030: 10 billion gge corn ethanol; up to 13.2 billion gge cellulosic thermochemical gasoline; up to 3.1 billion gge CTL; up to 4.6 billion gge GTL
Biofuels	Includes Reference biofuel availability plus additional drop-in biofuels: Up to 45 billion gge cellulosic thermochemical gasoline; 10 billion gge corn ethanol
AEO 2011 Electricity Grid	AEO 2011 Electricity Grid: 541 g CO_2e/kWh; 46% coal, 22% natural gas, 17% nuclear, and 12% renewable
Low-C Electricity Grid	AEO 2011 Carbon Price Grid: 111 g CO_2e/kWh; 6% coal, 25% natural gas, 12% natural gas w/CCS, 30% nuclear, and 23% renewable
Low-Cost H_2 Production	Lowest Cost: $3.85/gge H_2; 12.2 kg CO_2e/gge H_2; 25% distributed natural-gas reforming, 25% coal gasification, 25% central natural-gas reforming, and 25% biomass gasification
CCS H_2 Production	Added CSS: $4.10/gge H_2; 5.1 kg CO_2e/gge H_2; 25% distributed natural-gas reforming, 25% coal gasification w/CCS, 25% central natural-gas reforming with CCS, and 25% biomass gasification
Low-C H_2 Production	Low CO_2 emissions: $4.50/gge H_2; 2.6 kg CO_2e/gge H_2; 10% distributed natural-gas reforming, 40% central natural-gas reforming w/CCS, 30% biomass gasification, and 20% electrolysis from clean electricity

NOTE: CCS H_2 case analyzed by LAVE model, not VISION.

Technologies: A Focus on Hydrogen (NRC, 2008). There are two runs with the midrange vehicle fuel efficiencies, the first with low-cost hydrogen production (Low-Cost H_2 Production) and the second with low-GHG hydrogen production (Low-C H_2 Production), described in Table 5.1. Finally, there are two additional runs with optimistic assumptions about the fuel efficiency of FCEVs, each with the different assumptions for the GHG emissions from hydrogen production.

- *Emphasis on plug-in electric vehicles.* There are 4 VISION runs emphasizing plug-in electric vehicles (PEVs) to account for differences in assumptions about vehicle efficiency as well as GHG emissions impacts of the fuel. In all runs, the share of BEVs and PHEVs increases to about 35 percent of new LDV sales by 2030 and 80 percent by 2050, in line with the rates put forth in *Transitions to Alternative Transportation Technologies: Plug-In Hybrid Electric Vehicles* (NRC, 2010a). Relatively greater sales of PHEVs than BEVs in all years are assumed (see Table H.3 in Appendix H for details). Each of the two runs in each pair of runs—midrange and optimistic—uses a different assumption about GHG emissions from the electricity grid (AEO 2011 Grid and Low-C Electric Grid, Table 5.1). The low-emissions grid is assumed to emit 25 percent of GHGs per unit of generation compared to the BAU grid by 2050.
- *Emphasis on natural gas vehicles.* These runs assume that sales of compressed natural gas vehicles (CNGVs) are 25 percent of the market by 2030 and 80 percent by 2050. In both midrange and optimistic cases, CNG fuel use rises over time, and so little liquid fuel is needed by 2050 that it is assumed that no CTL and GTL plants are ever built. It is further assumed that RFS2 must be met by 2030, and so the liquid fuel that is used is primarily biofuels in both of these runs.

5.3.3 Results of Initial VISION Runs

Figures 5.5 to 5.7 indicate the results of the VISION model runs described above. The total amount of each type of fuel used in each scenario is shown in terms of energy use (billions of gallons of gasoline-equivalent). For the hydrogen and electricity cases, the fuels are not broken down by carbon content. Figure 5.5 shows results of the assumptions about fuel use that were made for the different VISION runs. For example, the total amount of liquid fuels used is the same for the Efficiency and Efficiency + Biofuels scenarios—it is assumed that it is the fraction of that fuel generated from biomass that is different. Higher prices for biofuels are likely to drive liquid fuel prices up over time and could result in less total liquid fuel used, but that type of market feedback cannot be accounted for in the VISION model runs.

Some ethanol and cellulosic biofuels are used in all of the scenarios because of the assumptions that they will be required under regulations such as RFS2. Over all of the scenarios, fuel energy use is lowest for the Plug-in Electric Vehicle, Hydrogen Fuel Cell Vehicle, and Optimistic Efficiency for ICEV and HEV cases.

Figure 5.6 shows that the long-term petroleum reduction goal of 80 percent by 2050 could occur if there is either (1) a major increase in biofuel availability with high-efficiency ICEVs (including HEVs) or (2) a large increase in alternatively fueled vehicles. All of the cases involving a transition to alternatively fueled vehicles meet or nearly meet a midterm petroleum reduction goal of 50 percent by 2030; in addition, optimistic ICEV efficiencies and widespread availability and use of biofuels could meet this interim goal as well. It is important to note that all of these scenarios assume very aggressive deployment of the specific vehicles and fuels being emphasized. The VISION model cannot address how these vehicle shares would be achieved. The model tells us nothing about how market conditions or policies would produce such results in vehicle and fuel shares.

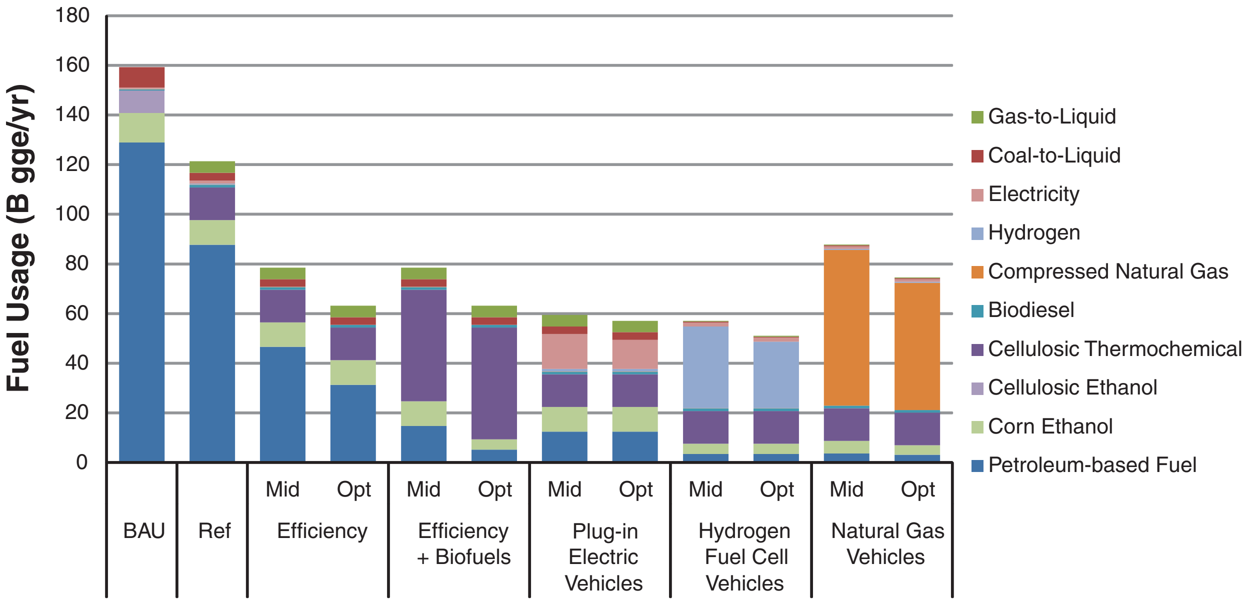
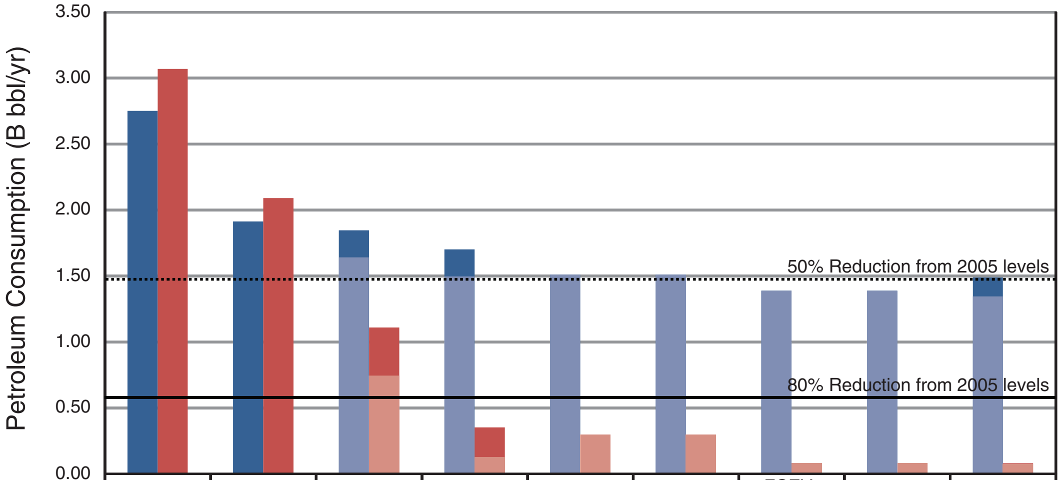


FIGURE 5.5 Fuel usage in 2050 for technology-specific scenarios outlined in Section 5.3.2. Midrange values are the committee's best estimate of the progress of the vehicle technology if it is pursued vigorously. Optimistic values are still feasible but would require faster progress than seems likely. No GTL or CTL fuel is used in the fuel cell and natural gas scenarios.

Figure 5.7 shows GHG emissions results for each scenario. It is noteworthy that all of the scenarios show substantial emissions reductions from the Committee Reference Case. However, meeting the 80 percent reduction goal is extremely difficult. Even given the aggressive deployment of advanced vehicle technologies and fuel supply technologies assumed in these runs, only two scenarios meet the 80 percent goal, the FCEV-dominated fleet powered by very low GHG-emitting hydrogen fuel and the optimistic case for vehicle efficiency plus biofuels. Several other scenarios come close to meeting the goal, and small reductions in VMT that could be expected with strict policies to reduce



	AEO BAU	Committee Reference	Efficiency	Efficiency + Biofuels	PEVs-AEO 2011 grid	PEVs-Low-C grid	FCEVs-Low-Cost H2	FCEVs-Low-C H2	CNGVs
■ 2030 Midrange	2.75	1.91	1.85	1.70	1.51	1.51	1.39	1.39	1.49
■ 2030 Optimistic			1.64	1.50	1.51	1.51	1.39	1.39	1.34
■ 2050 Midrange	3.07	2.09	1.11	0.35	0.30	0.30	0.08	0.08	0.08
■ 2050 Optimistic			0.75	0.12	0.30	0.30	0.08	0.08	0.08

FIGURE 5.6 U.S. light-duty vehicle petroleum consumption in 2030 and 2050 for technology-specific scenarios outlined in Section 5.3.2. Midrange values are the committee's best estimate of the progress of the vehicle technology if it is pursued vigorously. Optimistic values are still feasible but would require faster progress than seems likely.

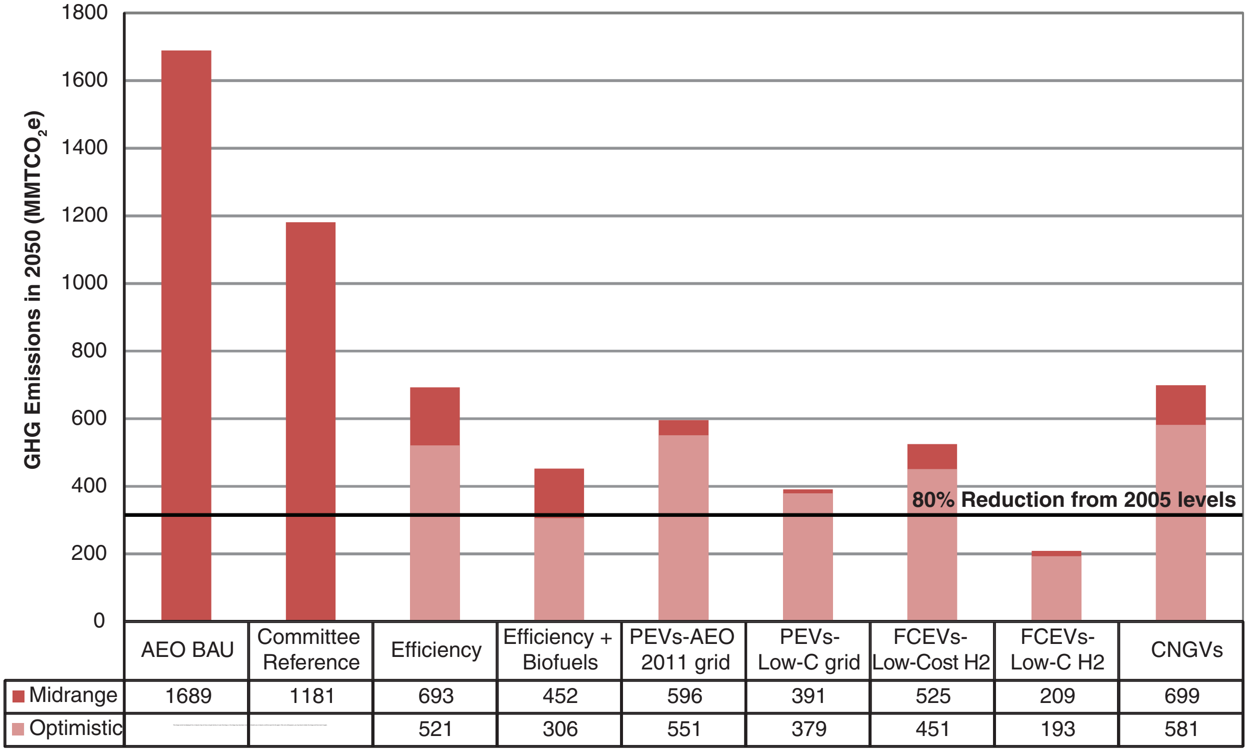


FIGURE 5.7 U.S. light-duty vehicle sector greenhouse gas emissions in 2050 for technology-specific scenarios outlined in Section 5.3.2. Midrange values are the committee's best estimate of the progress of the vehicle technology if it is pursued vigorously. Optimistic values are still feasible but would require faster progress than seems likely.

GHGs might be sufficient to push them to the 80 percent goal as well.

Although these model results illustrate penetration levels of certain vehicles and fuels that may achieve the petroleum usage and/or greenhouse gas emissions reductions desired, the VISION model does not estimate the cost or the policy actions that would be necessary. For this, an alternative approach is needed.

5.4 LAVE-TRANS MODEL

The LAVE modeling builds on the VISION analyses, illustrating how market responses may influence the task of achieving the petroleum and greenhouse gas reduction goals as well as providing a sense of the intensity of policies that may be required and measuring, very approximately, the costs and benefits. The committee recognizes that such estimates will be neither certain nor precise. Both market and technological uncertainty are very substantial, as is illustrated in Section 5.7, a fact that requires an adaptable policy process. However, ignoring market responses and the costs of necessary policies would be a mistake. The policy options included in the LAVE model are briefly summarized in Box 5.2 and described in greater detail in Section 5.4.2.

The analyses using the LAVE-Trans model proceed as follows. First, the LAVE-Trans and VISION model projections of the BAU case are compared to establish the general consistency of the two models. The LAVE-Trans model is then used to approximately replicate the VISION model scenarios, which again shows broad consistency but also some differences between the two models. The strategy and approach to policy analysis using the LAVE-Trans model are described next, including how costs and benefits have been measured. All of the policy scenarios described below include strict CAFE standards that are tightened over time, and also some policy approach to bring alternative fuels into the market, such as RFS2. In addition all policy scenarios below also include the Indexed Highway User Fee (IHUF).

- The first set of policy analyses explore what might be achievable by means of continued improvement of energy efficiency beyond 2025 and introduction of large quantities of "drop-in" biofuels with reduced greenhouse gas impacts produced by thermochemical processes. To provide incentives for greater efficiency from ICEs and HEVs, the first feebate policy in Box 5.2, the Feebate Based on Social Cost (FBSC) is introduced.
- A second set explores the potential impacts of policies that change the prices of vehicles and fuels to reflect the goals of reducing GHG emissions and petroleum use. In these model runs, stronger feebates

BOX 5.2
Policies Considered in the LAVE-Trans Model

Feebates Based on Social Cost (FBSC)—An approximately revenue neutral feebate system that precisely reflects the assumed societal willingness to pay to reduce oil use and GHG emissions (see Boxes 5.3, 5.4, and 5.5 on feebates and the values of GHG and oil reduction).

Indexed Highway User Fee (IHUF)—A replacement for motor fuel taxes, the IHUF is a fee on energy indexed to the average energy efficiency of all vehicles on the road and is designed to preserve the current level of revenue for the Highway Trust Fund (see Chapter 6 for details).

Carbon/Oil Tax—A gradually rising tax levied on fuels to reflect the societal values of their carbon emissions and petroleum content (see Boxes 5.4 and 5.5).

Feebates Based on Fuel Savings—A feebate system that compensates for consumers' undervaluing of future fuel savings. This feebate reflects the discounted present value of fuel costs (excluding the social cost fuel tax) from years 4 to 15, discounted to present value at 7 percent per year.

Transition Policies (Trans)—Polices that consist of subsidies to vehicles and fuel infrastructure designed to allow alternative technologies to break through the market barriers that "lock in" the incumbent petroleum-based internal combustion engine vehicle-fuel system. These could be either direct government subsidies or subsidies induced by governmental regulations, such as California's Zero-Emissions Vehicle standards.

on vehicles, those based on fuel savings, are included, and carbon and petroleum taxes are added that reflect estimates of the full social cost of using those fuels.

- The third, fourth, and fifth sets explore transitions from ICEVs fueled by petroleum to plug-in electric vehicles, fuel cell vehicles powered by hydrogen, and compressed natural gas vehicles, respectively. These all include transition policies tailored to the particular vehicle and fuel type being considered.
- Two final groups of cases consider combinations of PEVs and FCEVs and the implications of more optimistic technological progress. These also include the appropriate transition policies.
- Finally, the implications of uncertainty about technological progress and the market's response to advanced technologies and transition policies are considered. These cases include the IHUF, FBSC feebate, and transition policies while examining varied assumptions of technological progress and market behavior.

5.4.1 Comparing LAVE-Trans and VISION Estimates

As shown in Table 5.2, the BAU cases from the LAVE-Trans and VISION models confirm the general consistency of the two models. Each was calibrated to match in all years with respect to total vehicle miles of travel and total vehicle sales. There are differences in new-vehicle and vehicle stock fuel economies, the distributions of stock by age, and in the starting year GHG emissions rates due to the use of two different starting base years.[6] These lead to differences between the models of about 5 percent in energy and GHG emissions estimates in 2010, with the differences declining in subsequent years. This decline reflects the fact that the differences are chiefly due to the starting-year data for vehicle stocks and LDV energy efficiency and usage.

LAVE-Trans models vehicle purchase decisions and vehicle use in ways that VISION does not, enabling it to include market responses to improvements in vehicle technologies. If vehicles have fuel economy gains that are more than paid for by their fuel savings, for example, consumers will purchase more vehicles and the size of the vehicle stock will increase. If vehicle efficiency improves but fuel prices do not increase proportionately, vehicle use will increase. Market shares of vehicle technologies are not assumed in LAVE-Trans as they are in VISION but are based on a model of consumer choice that accounts for the prices, energy costs, and other attributes of the different technologies. All of these factors change a great deal over time in all cases.

The purchase prices and energy efficiencies of future vehicles strongly affect their market acceptance. In the LAVE-Trans model, novel technologies start out at a significant disadvantage relative to ICEV and HEVs because millions of these latter vehicles have already been produced and can access a ubiquitous infrastructure of refueling stations. Novel technologies must progress down learning curves by accumulating production experience and acquire scale economies through high sales volumes. As a result, the initial costs of BEVs, PHEVs, CNGVs, and FCEVs are much higher than the long-run costs projected in the midrange and optimistic scenarios. The long-run costs for passenger cars in Figure 5.8 show what is estimated to be technologically achievable in a given year at fully learned, full-scale production. In the midrange assessment, these potential costs converge between 2030 and 2040, with FCEVs and BEVs becoming slightly less expensive than ICEVs but with PHEVs remaining several thousand dollars more expensive. The optimistic assessment trends are similar but the convergence occurs more rapidly and the advantages of FCEVs and

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[6] The LAVE-Trans model has a starting year of 2010, while VISION uses a base year of 2005. Instead of reprogramming or recalibrating the models, it was checked simply that their estimates were consistent.

TABLE 5.2 Comparison of Business as Usual Projections of the VISION and LAVE-Trans Models

		2010		2030		2050	
		LAVE	VISION	LAVE	VISION	LAVE	VISION
Energy use	billion gge	132	126	137	129	158	159
Petroleum use	billion gge	124	120	118	115	129	129
Greenhouse gas emissions	MMTCO$_2$e	1,431	1,498	1,467	1,487	1,645	1,689
Vehicle sales	thousands	10,797	10,797	18,502	18,502	22,219	22,219
Vehicle stock	thousands	222,300	236,310	255,603	281,976	314,538	365,199
Vehicle miles traveled	trillion miles	2.73	2.73	3.75	3.75	5.05	5.05
New light-duty vehicle fuel economy	mpg	22.5	22.6	29.8	30.3	33.8	34.8
Stock light-duty vehicle fuel economy	mpg	20.6	21.2	27.4	27.8	32.0	31.7

BEVs are greater (see Figures 2.10 and 2.11 as compared with Figures 2.8 and 2.9).

The energy efficiencies of new vehicles are shown in the midrange case to continue to improve at a rapid rate beyond 2025 (see Table 2.12 for details). The new-vehicle fuel economy numbers are inputs to the LAVE-Trans model and are taken from the estimates presented in Chapter 2 after accounting for the difference between on-road and test-cycle values. Internal combustion engine cars (both gasoline and CNG) increase to over 90 mpg by 2050, while HEVs exceed 120 mpg. PHEV fuel economy is the same as HEV mpg when operating in charge-sustaining mode and the same as BEVs when operating in charge-depleting mode. Such large increases in energy efficiency mitigate the effects of fuel prices over time.

The prices of energy are also important and vary substantially among the cases examined below. Figure 5.9 shows the different assumptions about what influences the price of gasoline. The price depends not only on the level at which gasoline is taxed but also on the quantities of biofuel blended into it. Some included cases reflect the use of an IHUF on energy which increases very gradually over time as the average energy efficiency of all vehicles on the road increases. The greatest effect on pump prices, however, is with the introduction of a tax on the social value of carbon emissions and petroleum use, as described in Box 5.3, Box 5.4, and Box 5.5, assumed to be phased in over a period of 5 years. It is important to note that policies that greatly reduce the amount of oil used in the transportation sector, such as a number of those considered here, are likely to reduce both the demand for petroleum and its price. Less domestic use will mean fewer imports from insecure sources, which will likely reduce the magnitude of the social costs of using petroleum.

Figure 5.10 and Figure 5.11 show prices of other fuels under different assumptions. The price of electricity to consumers is affected by the de-carbonization of the grid, the IHUF, and the social value tax. Hydrogen prices start at more than $10/kg at low volumes and decrease as production approaches 6,000 tons/d. When and how quickly the decline occurs varies by scenario according to the level of hydrogen demand.

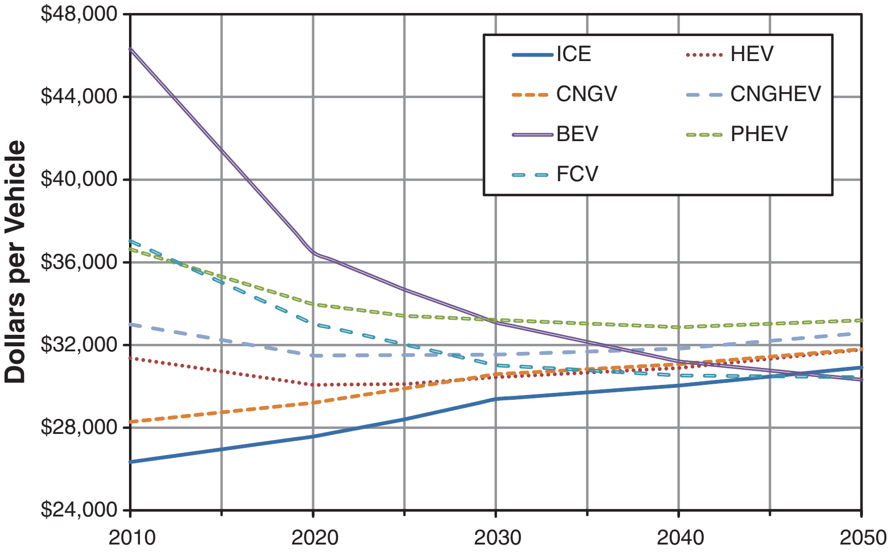

FIGURE 5.8 Fully learned, high-volume retail price equivalents (2009$) assuming midrange technology estimates.

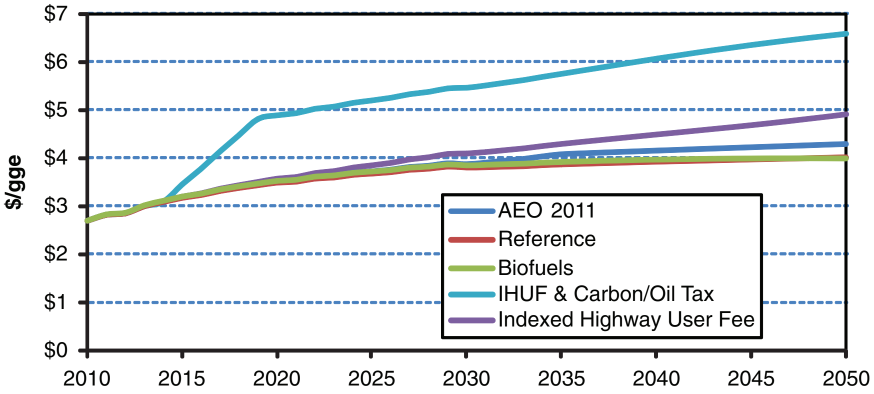

FIGURE 5.9 Retail prices of gasoline (in 2009$) under various policy assumptions.

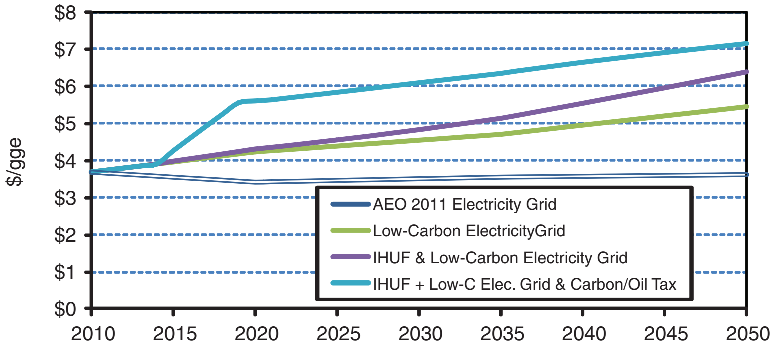

FIGURE 5.10 Retail prices of electricity (in 2009$) under various policy assumptions.

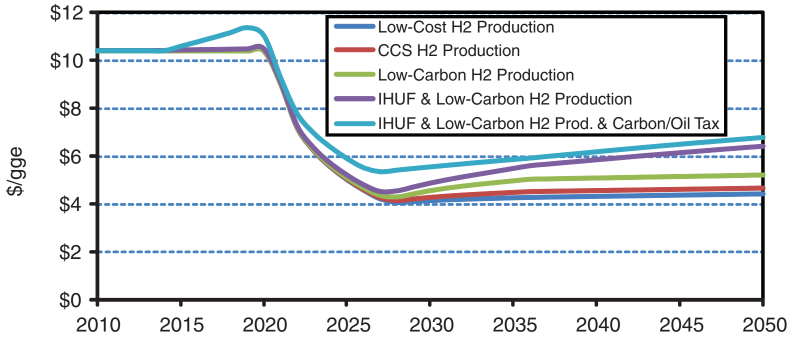

FIGURE 5.11 Retail prices of hydrogen (in 2009$) under various policy assumptions.

BOX 5.3
Feebates

Feebates are a fiscal policy aimed at influencing manufacturers to produce and consumers to purchase vehicles that are more energy efficient or produce fewer GHG emissions or both. A feebate system consists of a metric (e.g., g CO_2/mi, gge/mi), a benchmark, and a rate. Each vehicle is compared to the benchmark and is assigned a fee or a rebate according to the difference between its performance on the metric and the benchmark, multiplied by the rate. For example, if the metric is g CO_2/mi, the benchmark is 250 and the rate is \$20/(g CO_2/mi), a vehicle emitting 300 g CO_2/mi would pay a fee of \$1,000, whereas a vehicle emitting only 150 g CO_2/mi would receive a rebate of \$2,000. By carefully choosing the benchmark, the feebate system can be made approximately revenue neutral. Benchmarks can be defined in various ways, including as a function of a vehicle attribute, such as the footprint measure (wheelbase × track width) used in the current CAFE standards.

BOX 5.4
The Social Cost of Carbon Emissions

Twelve government agencies conducted a joint study of the social cost of carbon (SCC) to allow agencies to incorporate the social benefits of reducing carbon dioxide emissions into cost-benefit analyses (Interagency Working Group, 2010). The agencies used three well-known economic integrated assessment models (IAMs) to produce the estimates and considered a broad range of factors that affect the damage estimates. Their estimates for the years 2010 to 2050 (Table 5.4.1) represent the present value, in the year in question, of the discounted future damage resulting from a 1 metric ton increase in CO_2 emissions. Estimates are given for three different discount rates (5%, 3%, and 2.5%), and for a 95th percentile (5% probability) estimate from the models at a 3 percent discount rate.

The group provided the higher 95th percentile estimate because of the following important limitations of the current state of knowledge concerning future damage due to climate change:

1. Incomplete treatment of non-catastrophic damage
2. Incomplete treatment of potential catastrophic damage
3. Uncertainty in extrapolation of damage to high temperatures
4. Incomplete treatment of adaptation and technological changes, and
5. Assumption that society is risk neutral with respect to climate damage.

The interagency study strongly recommends using the full range of estimates in assessing the potential damage from climate change (p. 33). The range is an order of magnitude: from $4.70 to $64.90 per metric ton in 2010, rising to $15.70 to $136.20 per metric ton in 2050. In the committee's judgment, the 80 percent greenhouse gas mitigation goal reflects a societal willingness to pay that is most consistent with the highest, 95th percentile estimates. This is the value the committee refers to as the social value of reducing greenhouse gas emissions.

TABLE 5.4.1 Social Cost of CO_2, 2010-2050, in 2007 Dollars

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

SOURCE: Interagency Working Group (2010).

The market responses included in the LAVE model should make it somewhat more difficult to meet the GHG and oil reduction goals. To illustrate this, the LAVE model was used to approximately replicate the VISION model cases shown in Figures 5.6 and 5.7. The approach was to solve for the subsidies to alternative technologies that cause the LAVE model to predict the same market shares assumed in the corresponding VISION model run.[7] This solution method results in a net subsidy to vehicle sales which over time will increase the size of the vehicle stock and thereby increase vehicle travel and energy use. In reality, the same market shares could be achieved by cross-subsidizing vehicles, which would reduce the impact on vehicle sales (e.g., via feebates; see Box 5.3). In that respect, the method will tend to exaggerate the greater difficulty of meeting the GHG and petroleum goals as a consequence of market responses.

In most cases the models produced very similar reductions in petroleum use and GHG emissions (Figure 5.12) with the LAVE-Trans model predicting somewhat smaller reductions, as expected. In most cases the differences are on the order of 5 percentage points. The VISION and LAVE-Trans CNGV

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[7] Only the key market shares were carefully matched. For example, in the PEV cases the market shares for battery electric and plug-in hybrid electric vehicles were matched; the remaining technologies' market shares were as predicted by the LAVE model. In the FCEV cases only the market shares of fuel cell vehicles were closely matched.

BOX 5.5
Social Costs of Oil Dependence

The costs of oil dependence to the United States are caused by a combination of:

1. The exercise of monopoly power by certain oil-producing states,
2. The importance of petroleum to the U.S. economy, and
3. The lack of ready, economical substitutes for petroleum.

Costs exceed those that would prevail in a competitive market due to the use of market power chiefly by nationalized oil exporters. The direct economic costs of oil dependence can be partitioned into the following three, mutually exclusive components (Greene and Leiby, 1993):

1. Disruption costs, reductions in gross domestic (GDP) due to price shocks,
2. Long-run GDP losses due to higher than competitive market oil prices,
3. Transfer of wealth from U.S. oil consumers to non-US oil producers via monopoly rents.

When the U.S. takes actions to reduce its oil demand the world demand curve contracts resulting, other things equal, in lower world oil prices.[1] Such use of monopsony power counteracts the use of monopoly power, increasing U.S. GDP and reducing the transfer of U.S. wealth to non-U.S. oil producers. Individuals will generally not consider the fact that reducing one's own oil consumption produces benefits to others via lower oil prices. As a consequence the social benefits of reducing oil consumption exceed the private benefits. Although this appears to be similar to an externality, it is not an externality. The National Research Council (2009a) report *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* considers only external costs and thus provides no relevant guidance on the value of reducing oil consumption.

Sudden, large movements in oil prices can temporarily reduce U.S. GDP by creating disequilibrium in the economy, leading to less than full employment of capital and labor (Jones et al., 2004). A substantial econometric literature on this subject has identified an important impact of price shocks on U.S. economic output (e.g., Huntington, 2007; Brown and Huntington, 2010). Reducing oil consumption reduces vulnerability to price shocks.

The Environmental Protection Agency and the National Highway Traffic Safety Administration (EPA and NHTSA, 2011) have published estimates of disruption costs as well as the monopsony effect. The estimates, based on Leiby (2008), recognize uncertainty about future oil market conditions and other parameters and are therefore specified as ranges that vary by year (Table 5.5.1). The range of total social costs per barrel is approximately $10 to $30, with the midpoint estimates lying close to $19 per barrel. If U.S. petroleum use decreases over time in accord with the reduction goals set for this study, the value of the monopsony benefit will also decrease. It is assumed that it will be halved by 2050.

cases differ a good deal, chiefly because the VISION model included both ICE and HEV CNGVs while the LAVE model was capable of including only ICE CNGVs. In both models BEVs are assumed to be used only 2/3 as much as other vehicles. The "missing miles" are allocated 60 percent to other existing vehicles, 30 percent to trips not taken (reduced VMT), and 10 percent to increased vehicle sales.

The vehicle and infrastructure subsidies estimated to be necessary to achieve the market shares assumed for the VISION model are very large (subsidies are shown in Figure 5.13 as negative values). The LAVE-Trans model was used to estimate the per-vehicle subsidies required to achieve the market shares for alternative technologies assumed in the VISION runs. No assumption was made about who would pay for the subsidies. For the CNGV and FCEV cases, it was assumed that 300 subsidized refueling stations would be deployed to support initial vehicle sales. Inferred subsidies for five runs using midrange technology assumptions are in the range of $35 billion to $45 billion annually by 2050 (values discounted to present value at 2.3 percent per year[8]). Cumulative subsidies run to hundreds of billions of dollars. Although per-vehicle subsidies are larger in the earlier years, fewer vehicles are being sold so that total subsidies are smaller. The VISION CNGV sales through 2030 are somewhat lower than the LAVE-Trans model would predict in the absence of subsidies, and so small taxes on CNGVs (positive values in Figure 5.13) are needed to match the VISION assumptions. For the most part, the very large subsidies are a consequence of assuming market shares for the 2030 to 2050 period that are substantially higher than the LAVE-Trans model estimates the market would sustain without continuing subsidies. The next section explores what might be possible with temporary subsidies that are sufficient to break down the transition barriers but can be quickly phased out once those barriers have been breached.

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[8] OMB Circular No. A-94 specifies discount rate for projects up to 30 years, whereas the time-frame for this analysis is 40 years. The recommended rate for 20-year projects is 1.7 percent and for 30-year projects is 2.0 percent (OMB, 2012).

TABLE 5.5.1 Oil Security Premiums, Midpoint, and (Range) by Year (2009 $/barrel)

Year	Monopsony	Disruption Costs	Total
2020	$11.12 ($3.78–$21.21)	$7.10 ($3.40–$10.96)	$18.22 ($9.53–$29.06)
2025	$11.26 ($3.78–$21.48)	$7.77 $3.84–$12.32)	$19.03 ($9.93–$29.75)
2030	$10.91 ($3.74–$20.47)	$8.32 ($4.09–$13.34)	$19.23 ($10.51–$29.02)
2035	$10.11 ($3.51–$18.85)	$8.60 ($4.41–$13.62)	$18.71 ($10.30–$28.20

SOURCE: EPA and NHTSA (2011), Table 4-11.

The estimates in Table 5.5.1 do not include military costs (EPA, NHTSA, 2011, p. 4-32), yet access to stable and affordably priced energy has traditionally been considered a critical element of national security (e.g., McConnell, 2008, p. 41; Military Advisory Board, 2011, p. xi). Estimates of the national defense costs of oil dependence range from less than $5 billion per year (GAO, 2006; Parry and Darmstadter, 2004) to $50 billion per year or more (Moreland, 1985; Ravenal, 1991; Kaufmann and Steinbruner, 1991; Copoulos, 2003; Delucchi and Murphy, 2008). Assuming a range of $10 billion to $50 billion per year, and dividing by a projected consumption rate of approximately 6.4 billion barrels per year (EIA, 2012, Table 11) gives a range of average national defense cost per barrel of $1.50 to $8.00 per barrel (rounded to the nearest $0.50).

Adopting the EPA-NHTSA estimates indicates a range of about $9 to $30 per barrel, with a midpoint of $19. A reasonable range of national defense and foreign policy costs appears to be $1.50 to $8 per barrel, with a midpoint of about $5 per barrel. Adding these numbers produces a range of $10.50 to $38 per barrel with a midpoint of $24 in 2009$, or about $25 per barrel in current dollars. This is the value adopted by the committee to reflect the social value of reductions in petroleum usage.

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[1] Since OPEC is not a competitive supplier, there is no world oil supply function in the usual sense. The response of world oil prices to a reduction in U.S. demand will therefore depend on how OPEC reacts. OPEC's options, however, are not unlimited. If OPEC does not reduce output, oil prices will fall. If OPEC does reduce output, it loses market share which diminishes its market power. Greene (2009) has shown that in terms of economic benefits to the U.S. there is very little difference between the two strategies.

5.4.2 Analysis of Transition Policy Cases with the LAVE-Trans Model

Given the committee's fuel and vehicle technology scenarios, the LAVE model was used to estimate what might be accomplished by policies that reflect the social value of reducing GHG emissions and petroleum use combined with additional but temporary policies to induce transitions to alternative vehicles or fuels or both. Policies that reflect the value of reducing GHG emissions and petroleum use are initiated in 2015 or 2017 and remain in effect through 2050.[9] The current subsidies for electric and fuel cell vehicles are assumed to end by 2020 and be replaced by the new policies. Policies to induce transitions to alternative vehicle and fuel combinations begin at various dates and are phased out once the alternative technologies achieve a sustainable market share. Their intended function is to overcome the barriers to a transition from the incumbent energy technology to an alternative. Transition policies consist of explicit or implicit vehicle and infrastructure subsidies. Implicit subsidies would result from policies such as California's Zero Emission Vehicle (ZEV) mandates that require manufacturers to sell ZEVs regardless of market demand and therefore to cross-subsidize ZEVs. Or, requiring fuel providers to provide refueling outlets for alternative fuels would induce cross-subsidies from petroleum fuels to low-carbon alternatives. Similarly, policies such as RFS2 to require certain amounts of biofuels are an example of an implicit subsidy for alternative fuels.

At present, there is both uncertainty and disagreement about the value of reducing petroleum consumption and the value of reducing greenhouse gas emissions. The committee's approach is to value these reductions according to society's willingness to pay, as reflected in the stringency of the reduction goals. For example, carbon emissions should be valued at a cost consistent with the cost of de-carbonizing the electric utility sector as discussed in Chapter 3 and described in greater detail in Box 5.4. For GHG mitigation, the commit-

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[9] The feebate system reflecting the social value of reductions in CO_2 emissions and petroleum use begins in 2017 while all other fiscal policies, if used, begin in 2015.

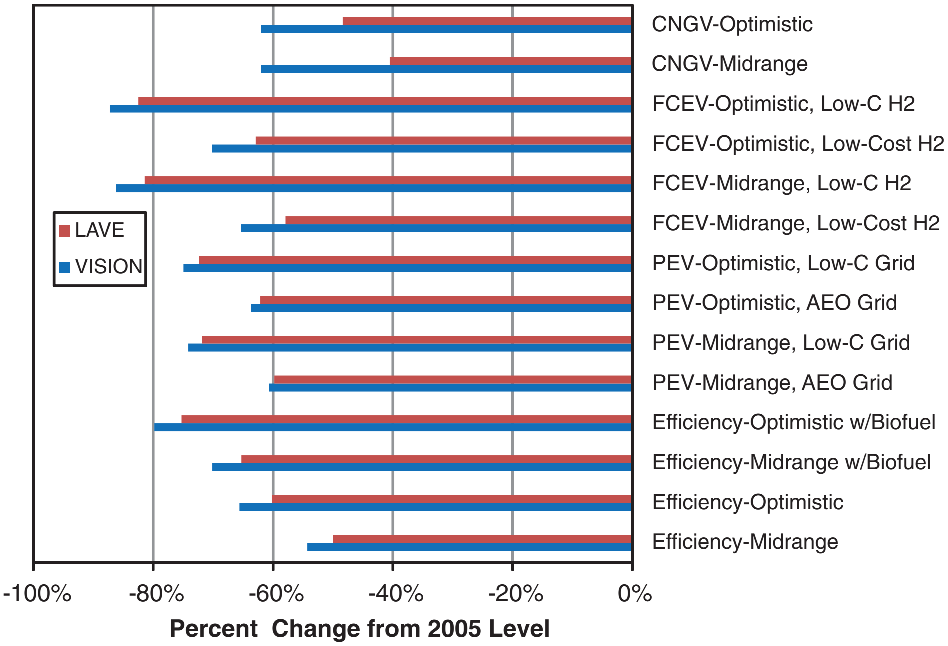

FIGURE 5.12 Comparison of LAVE-Trans and VISION model-estimated GHG reductions in 2050 given matching deployment.

tee elected to adopt the highest estimates of the Interagency Working Group on the Social Cost of Carbon (2010), and for petroleum reduction the committee derived its own estimates based on research by Leiby (2008) and others (see Box 5.5). These assumed values are shown in Figure 5.14.

Policies consistent with a strong commitment to reduce oil use and GHG emissions are included in all the policy cases. Specifically, a steady tightening of CAFE/GHG emissions standards combined with associated policies is assumed to ensure that they are met and enforced, which would yield efficiency improvements of both the midrange and optimistic vehicle technology scenarios, as explained in Chapter 2. Because the fuel economy and emissions standards will almost certainly be a binding constraint on manufacturers' technology and design decisions, they will induce manufacturers to price the different drive train technologies so as to reflect their contributions to meeting the standards. This is represented by an approximately revenue-neutral feebate system that precisely reflects the social value of reductions in petroleum use and GHG emissions (see Boxes 5.3, 5.4, and 5.5 on feebates and the values of GHG and oil reduction).

Policies such as the RFS2, Low Carbon Fuels standards, or equivalent will be needed to bring drop-in biofuels to market, and additional policies will be required to ensure that electricity or hydrogen is produced via methods with

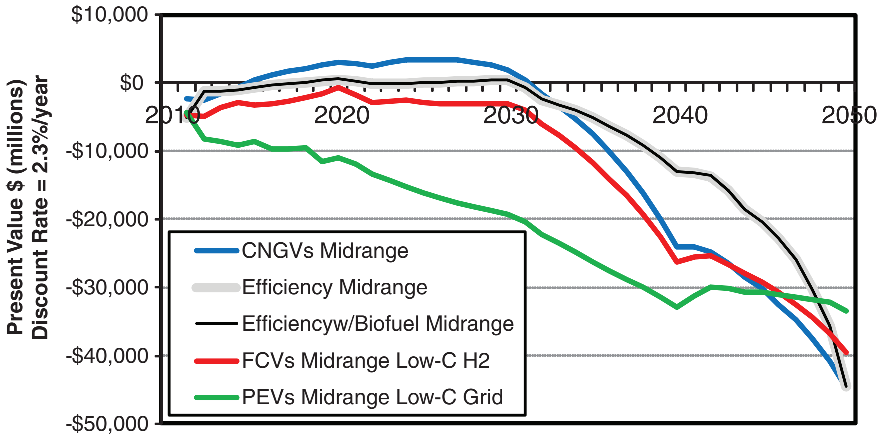

FIGURE 5.13 Annual subsidies to alternative fuels vehicles required to match five VISION cases. Negative values represent a net cost. The two efficiency curves are overlapping but not identical because the vehicle costs are the same and fuel costs nearly the same.

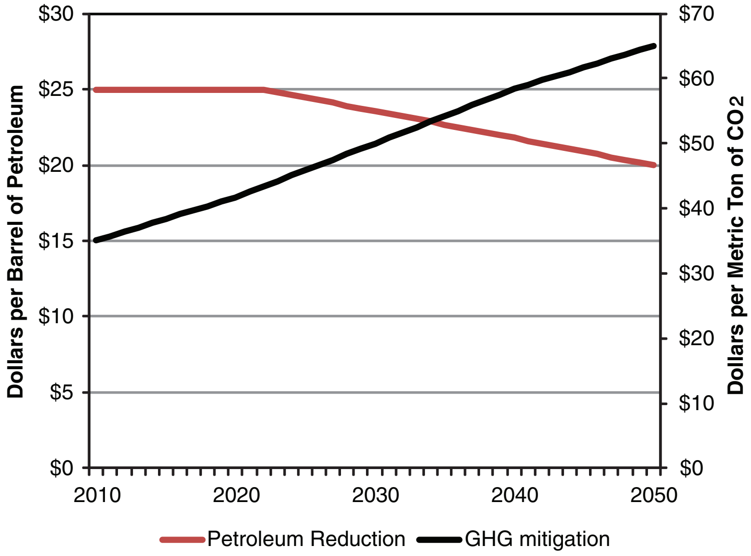

FIGURE 5.14 Assumed social values of reductions in GHG emissions and petroleum usage (in 2009$).

reduced greenhouse gas impacts, as explained in Chapter 3. These policies are implicit in all model runs except the BAU and Reference Cases. Their costs are reflected in the prices of the fuels for those cases assuming fuels produced with reduced GHG impacts (e.g., "+ Low-C Grid"). In addition, the very large improvements in energy efficiency included in all the policy runs will severely reduce Highway Trust Fund revenues unless measures are taken to prevent it. All policy cases assume that motor fuel taxes will be replaced by a user fee on energy (IHUF), indexed to the average energy efficiency of all vehicles on the road (see Chapter 6 for details).

Two additional fiscal policies were considered. A tax can be levied on fuels reflecting the social costs of their carbon emissions and petroleum content. When this tax is used, the feebates reflecting the social value of carbon emissions reductions are reduced. Since the vehicle choice model includes the first 3 years of fuel costs, the fuel taxes paid in those years will be taken into account by consumers in their vehicle purchase decisions. Thus, the feebate rates are adjusted to include only the social values of reductions in carbon emissions and oil use in the remaining years of the vehicle's life. The impact of the fuel tax is therefore on vehicle use rather than vehicle choice. The remaining fiscal policy is an additional feebate system that compensates for consumers' undervaluing of future fuel savings. This feebate reflects the discounted present value of fuel costs (excluding the social-cost fuel tax) from years 4 to 15, discounted to present value at 7 percent per year.[10]

5.4.2.1 Transition Policies

A transition to an alternative vehicle and fuel combination such as fuel cells and hydrogen or plug-in electric vehicles may be necessary to meet the reduction goals. This section focuses on such a transition away from the incumbent petroleum-based, ICEV-fuel system. As seen in the VISION results and again below, it may also be possible that the goals can be met without a transition to hydrogen- or electricity-powered vehicles. A shift away from petroleum fuel toward drop-in biofuels, combined with much more efficient ICEV and HEV engines, also offers an opportunity for significant greenhouse gas and petroleum reductions by 2050, although the 2030 petroleum reduction target remains difficult to achieve in all cases. With the data and model available, the committee is not able to fully explore the transition to large-scale low-carbon biofuels production here but does examine this case with the available information below.

In the LAVE model, transition polices consist of subsidies to vehicles and fuel infrastructure. These could be either direct government subsidies or subsidies induced by governmental regulations, such as California's ZEV standards. The function of these subsidies is to allow alternative technologies to break through the market barriers that "lock-in" the incumbent petroleum-ICEV vehicle-fuel system. The transition policies used in the policy cases have been constructed by following these rules:

1. Annual sales in the first 3 to 5 years of a transition should number in the thousands to tens of thousands of units.
2. The increase in sales in any year should not be more than 6 percent of total light-duty vehicle sales.

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[10] OMB Circular No. A-94 recommends a discount rate for private return on capital of 7 percent (OMB, 2012).

3. The growth of sales should avoid abrupt increases or decreases.
4. Subsidies should be phased out as sales approach the level the market will support without subsidies.

In reality, a transition policy would need to be more comprehensive. Transition policies could potentially offer a greater variety of incentives, such as access to high occupancy vehicle lanes, free parking in congested areas, and so on. In the LAVE model the vehicle and fuel subsidies are intended to measure the cost of inducing transitions rather than to describe the specific polices by which they should be accomplished.

5.4.2.2 Transition Costs and Benefits

The costs and benefits of each of the policy cases presented below are measured relative to a Base Case that includes identical assumptions about technological progress and all other factors but does not include new policies to induce a transition to alternative vehicles or fuels or both. This was done to better measure the incremental costs and benefits of accomplishing transitions to alternative vehicles and fuels, as distinguished from the obvious benefits of having better technology. In general, this means that if the midrange technology assumptions are used in a transition case, the transition case will be compared to a Base Case that also uses the midrange technology assumptions. If a transition case uses optimistic assumptions for some technologies and midrange assumptions for others, its Base Case will make identical assumptions about technological progress. The transition cases differ from their respective Base Case only in terms of the transition policies. Except for the BAU and Reference Cases, all Base Cases assume that fuel economy and emissions standards are continuously tightened through 2050.

Costs and benefits are measured[11] as changes from the respective Base Case in the following five quantities:

1. Costs of subsidies,
2. Additional fuel costs or savings,
3. Changes in consumers' surplus,
4. The social value of GHG reductions, and
5. The social value of reduced oil use.

- *Subsidy costs* include the implicit or explicit vehicle subsidies due to the higher costs of more efficient vehicles with lower greenhouse gas emissions, and they include the cost of subsidized infrastructure for public recharging of plug-in electric vehicles or refueling hydrogen or CNG vehicles.
- *Additional fuel costs or savings.* Since consumers are assumed to consider only the first 3 years of fuel savings in making their vehicles choices, it is necessary to account for the additional costs or savings over the remainder of each vehicle's lifetime. Additional fuel costs or savings are private costs or benefits that accrue to the vehicle user that (by assumption) are not capitalized by the vehicle purchaser at the time of purchase.
- *Consumers' surplus* is an economic concept that measures consumers' welfare in dollars. Two changes in consumers' surplus are measured: (1) satisfaction with vehicle purchases and (2) satisfaction with fuel purchases. The LAVE model includes a widely used method of modeling consumer choice that recognizes that not all consumers have the same tastes or preferences. Some may prefer the attributes of electric drive while others prefer internal combustion engines. If electric-drive vehicles become available at competitive prices as a result of successful transition policies, the satisfaction of those with a preference for electric drive will increase. Those who prefer ICEVs will still have that option and so will be no better or worse off than before the plug-in vehicles became available. Consumers' surplus measures that increased value in dollars. Vehicle subsidies increase consumers' surplus but by less than the gross amount of the subsidies. This results in a net economic cost, at least in the early years of a transition. Taxing the energy consumers must purchase to operate their vehicles creates a loss of consumers' surplus, in addition to a transfer of wealth from consumers to the taxing entity. The surplus loss over and above what is counted in the vehicle purchase decision is also measured when changes in tax policies are considered.
- *The social value of reducing greenhouse gas emissions and oil use.* These values are measured by multiplying the changes in estimated annual quantities times the social cost of emissions per unit assumed by the committee consistent with the goals of the study (see Boxes 5.4 and 5.5). Hydrogen and fuel cell vehicles will also have zero tailpipe emissions of other pollutants, and may have lower full fuel cycle emissions, as well. The committee has not attempted to estimate those potential benefits, and they are not included in the cost and benefit estimates.

The net present value (NPV) of a policy case is the sum of all costs and benefits from 2010 to 2050, plus the fuel, GHG, and petroleum costs and benefits of vehicles sold through 2050 that will still be in use beyond that date. From an economic perspective, an optimal policy strategy would be one that maximized NPV. NPV depends strongly on the discount rate assumed, and there may be widely differing opinions about the appropriate discount rate. A 2.3 percent rate for

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[11] All costs and benefits are measured in constant dollars, discounted to present value using an annual discount rate of 2.3 percent.

all years is used, which is consistent with the most recent guidance of the U.S. government (OMB, 2012); however, the appropriate discount rate is yet another source of uncertainty.

Sections 5.4.3 to 5.4.9 present results from transition policy cases and compare them to their respective Base Cases. In general, all cases (except BAU and Reference) assume fuel economy/emissions standards to 2050. All cases (except BAU and Reference) include feebates and the IHUF. All transition cases assume vehicle subsidies or mandates and infrastructure subsidies or mandates. A few of the cases add special policies as noted in the text.

Rather than enabling us to reach definitive conclusions, the committee's modeling suggests the extent of technological progress and the kinds and stringency of policy measures that are likely to be needed to bring about transitions. It provides useful insights about the interactions between policy, the market, and technological changes. It also provides a general indication of the costs and benefits of achieving the GHG and petroleum reduction goals conditional on the many assumptions that must be made. Uncertainty will be an inherent property of the process of energy transition: uncertainty about technological change, uncertainty about the market's response to technologies and policies, and uncertainty about the future state of the world. The extent of uncertainty about both future technologies and the market's response to them is illustrated by means of sensitivity analysis in Sections 5.6 and 5.7 below.

5.4.3 Energy Efficiency Improvement and Advanced Biofuels

The cases described in this section explore what may be possible given the midrange and optimistic technology projections, continued tightening of fuel economy and emissions standards, and large-scale production of thermo-chemically produced "drop-in" biofuels. These cases maintain the ICEVs with improved technology but involve a transition to large scale production and use of cellulosic biofuels. A final case also includes adoption of all the pricing policies described above. All cases include the IHUF, which increases from $0.42/gge in 2010 to $1.27/gge in 2050, and feebates that reflect the assumed societal willingness to pay for reductions in GHG emissions and oil use.

The technological progress enabling increased energy efficiency described in Chapter 2 (Table 2.11) will be devoted to improving vehicle fuel economy only if strong policies, such as increasingly stringent fuel economy and emissions standards, are put in place beyond 2025. The approximately revenue-neutral feebates, which are phased over 5 years beginning in 2017, amount to a tax of $60 per ICEV in 2021, with rebates of $770 per HEV, $1,650 per PHEV, $2,900 for each BEV, and $2,575 per FCEV. The feebates change over time as energy efficiencies, fuel properties, and the social willingness to pay for GHG and oil use reductions change. Assuming such standards are implemented, the midrange estimates of efficiency improvements and their costs result in estimated reductions in GHG emissions of 29 percent by 2030 and 52 percent by 2050 (Figure 5.15). For the same dates, petroleum consumption is estimated to be reduced by 33 and 64 percent, respectively. The reductions are due in part to the continued reduction in rates of fuel consumption for both ICEVs and HEVs (Figure 5.16) and by a steady shift from ICEVs to HEVs and BEVs (Figure 5.17).

If technology progresses as envisioned in the midrange scenario, the economic benefits of the efficiency improvements versus the Business as Usual case could be very large.

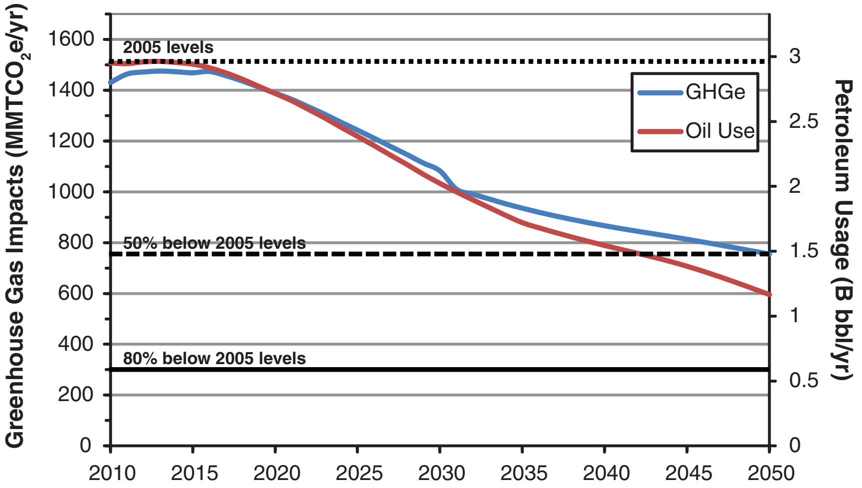

FIGURE 5.15 Changes in petroleum use and greenhouse gas (GHG) emissions for the Efficiency case with midrange technology estimates as compared to 2005 levels.

The key components of economic costs and benefits are shown in Figure 5.18 as annual costs, discounted to present value at the rate of 2.3 percent per year. The sum of the individual components grows to an estimated $130 billion per year by 2050. The largest component is "uncounted fuel savings," the future fuel savings not considered by consumers at the time of purchasing a new car but realized later over the life of the vehicle. Consumers' surplus, their net satisfaction with their vehicle purchases, decreases slightly after 2030 due to the increased cost of ICEVs over time. The net present social value of the transition to much higher efficiency vehicles is estimated to be on the order of $3.5 trillion.

Increasing the quantity of thermochemically produced, drop-in biofuels from 13.5 billion gge to 19.2 billion gge in 2030 increases the estimated reduction in petroleum use from 33 to 37 percent in that year. The 2030 reduction in GHG emissions is 32 percent versus 28 percent. In 2050, when the biofuels industry has expanded to produce 45 billion gge, the estimated impact is much greater: petroleum use is down 86 percent (compared with 64 percent) and GHG emissions are 66 percent lower than in 2005 (compared with 52 percent without advanced biofuels) (Figure 5.19).

If carbon emissions from the production of 20 percent of thermochemical biofuels were captured and stored, an estimated 78 percent reduction in GHG emissions versus

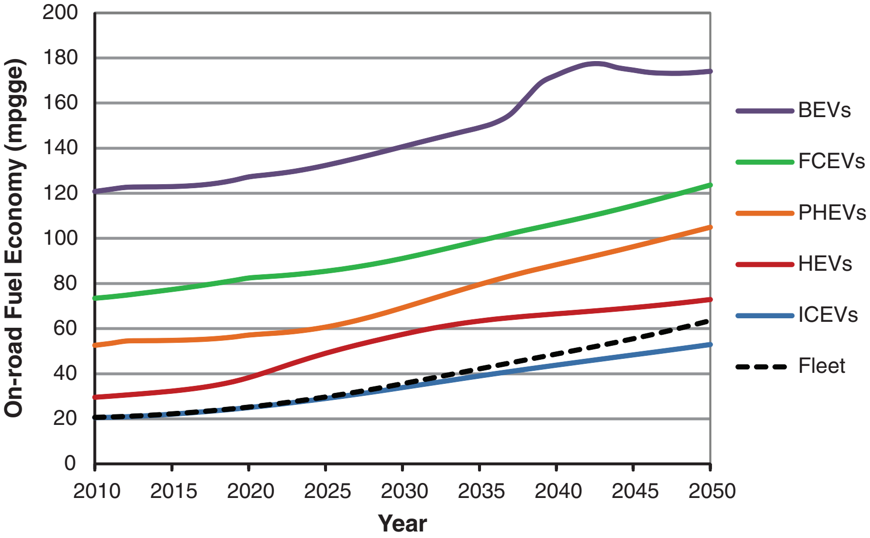

FIGURE 5.16 Average fuel economy of on-road vehicles for the Efficiency case with midrange technology estimates. The upturn in battery electric vehicle (BEV) fuel economy after 2040 reflects the rapidly increasing share of new BEVs on the road (and thus a larger fraction of the BEV fleet is the newest, most efficient BEVs). The downturn that follows is representative of an increasing number of battery electric trucks in the fleet.

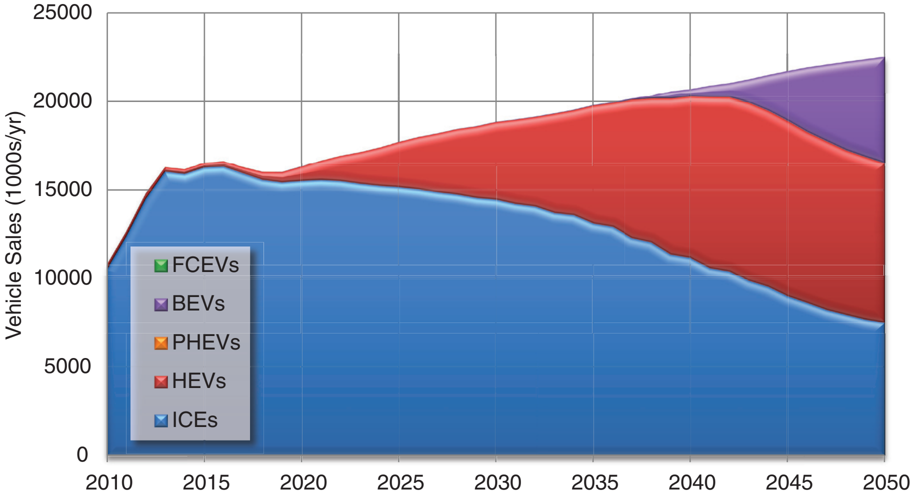

FIGURE 5.17 Vehicles sales by vehicle technology for the Efficiency case with midrange technology estimates.

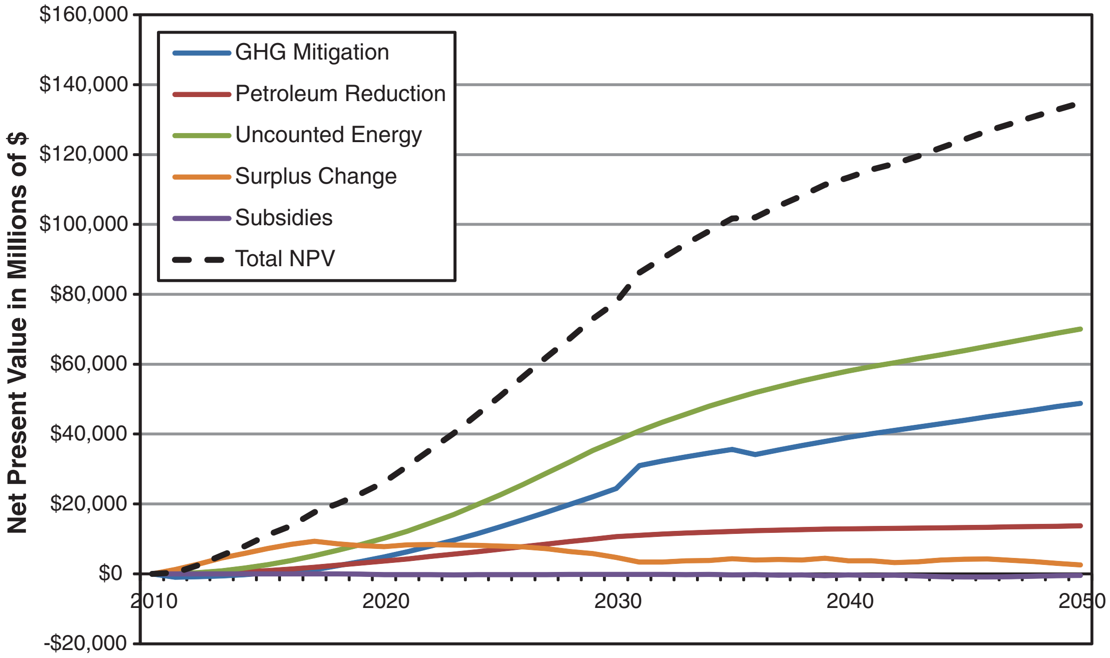

FIGURE 5.18 Estimated costs and benefits for the Efficiency case with midrange technology estimates.

2005 could be achieved by 2050. Given the uncertainty in the analysis, the 2050 goals would then be met for all practical purposes. The 2030 goal of a 50 percent reduction in petroleum use is still missed because of the low initial ramp-up in production, however; the estimated reduction is 37 percent. The cost of 20 percent CO_2 removal for biofuels blended into gasoline adds about $0.20 per gallon to the average price of gasoline in 2050. If CCS is applied to all biofuels, then the net GHG emissions from the LDV fleet could be slightly negative.

5.4.4 Emphasis on Pricing Policies

A great deal can be accomplished by means of policies that change the prices of fuels and vehicles and harness market forces to reduce GHG emissions. This scenario, like the others based on the midrange technology scenario, assumes that fuel economy standards are inducing manufacturers to produce increasingly efficient vehicles. However, it also introduces stronger feebates and adds to the cost of fuels the social willingness to pay for GHG and oil reduction. The additional feebate system capitalizes in vehicles' prices the uncounted energy savings due to consumers' assumed under-

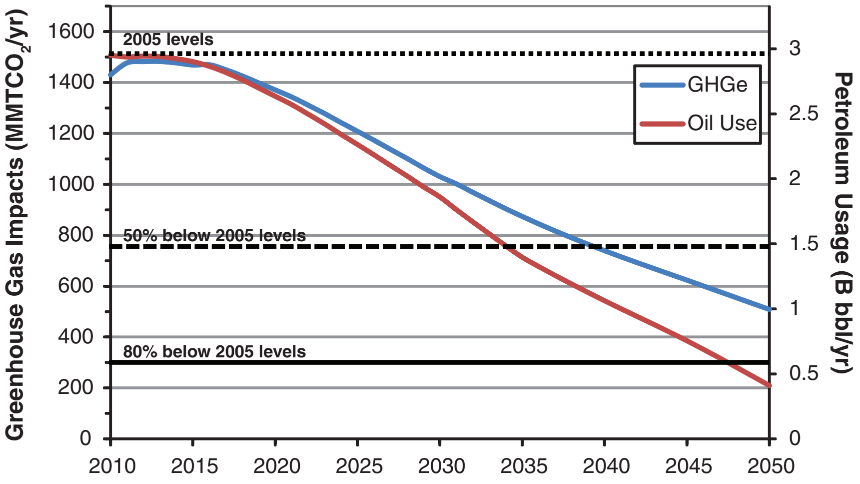

FIGURE 5.19 Changes in petroleum use and greenhouse gas (GHG) emissions for the Efficiency + Biofuels case as compared to 2005 levels.

valuing of future fuel savings.[12] Production of electricity and hydrogen via processes with low-GHG impacts is assumed, but not intensive use of drop-in biofuels.

The fully taxed price of gasoline increases from $2.70 per gallon in 2010 to $4.90 per gallon in 2020 and $5.50 per gallon in 2030. Gasoline prices continue to increase, reaching $6.60 per gallon in 2050, as a result of $2.70 per gallon in combined taxes. The price of electricity in 2050 is roughly equal to that of gasoline on an energy basis, but BEVs are more than three times more energy efficient than comparable ICEVs in 2050. Feebates also strongly encourage purchases of BEVs. The rebate for a BEV in 2020 is almost $14,000, while ICEVs are taxed at $300 each. The difference decreases as vehicles and fuels improve so that by 2050, BEVs receive a $1,300 per vehicle rebate, whereas ICEVs are taxed at $2,500 per vehicle (the incidence also shifts to approximate revenue neutrality).

The result is a massive shift to battery electric and hybrid electric vehicles. By 2050, an estimated 59 percent of new-vehicle sales are BEVs and 33 percent are HEVs. In 2050 almost 40 percent of the vehicles on the road are BEVs. In the absence of policies to put a hydrogen refueling infrastructure in place, fuel cell vehicles never achieve any significant share of the market. Battery electric vehicles are far less dependent on early infrastructure development, which gives them a decisive advantage over FCEVs in this scenario.

Light-duty vehicle petroleum use is estimated to be 38 percent lower than the 2005 level by 2030, and 87 percent below 2005 in 2050. Greenhouse gas emissions are reduced 74 percent by 2050. Vehicle miles of travel in 2050 are also more than 15 percent lower than in the Efficiency Case (identical assumptions but without the additional pricing policies). In part this is due to the higher energy prices, but it is also due to 7 percent fewer vehicles on the road and lower annual miles for the 39 percent of vehicles that are BEVs.

5.4.5 Plug-in Electric Vehicles

Plug-in electric vehicles (PEVs) possess some attributes that are substantially different from those of the other vehicle types. Battery electric vehicles (BEVs) not only have limited range but also have long recharging times. The combination of these two attributes limits the ability of BEVs to satisfy all the daily travel demands of most drivers. This reduces the total annual mileage of BEVs to two thirds of that of an ICEV, HEV, CNGV, or FCEV and detracts from their utility to most households. In the LAVE-Trans model, most but not all of the vehicle travel demand that cannot be satisfied by BEVs is shifted to other vehicles in the vehicle stock. To some degree the BEV's travel range limitations will be offset by its lower energy costs. In the midrange technology scenario, the long-run, fully learned cost of BEVs is $20,000 more than that of ICEVs in 2010, although BEVs eventually become $600 less expensive by 2050 (see Figure 5.8). PHEVs, on the other hand, suffer no such limitations on use and can take energy from the grid or from the gas pump. However, their initial cost is higher and remains higher through 2050 in the midrange scenario. PHEVs start out with a high-volume, learned cost that is $10,000 more than that of an ICEV and remains at least $2,000 more expensive through 2050. The PHEV's higher price will be partly offset by lower energy costs, yet its price remains a significant barrier to full market success.

Two PEV transition policy scenarios are reported below. Both include feebates reflecting social willingness to pay for GHG and petroleum reduction plus the IHUF. In the first, PHEVs achieve a modest market share of 5 percent whereas BEVs account for 35 percent of new-car sales by 2050. The scenario continues the current levels of PHEV and BEV sales, which requires substantial, sustained subsidies: total subsidies per BEV decrease from $25,000 per vehicle in 2012 to just over $10,000 per vehicle in 2020.[13] When long-run PEV costs approach the prices of other technologies the transitional subsidies are removed (2028 for BEVs and 2033 for PHEVs) but the feebates and IHUF continue. By 2050, PEVs constitute 40 percent of the market, HEVs 34 percent, and advanced ICEVs 26 percent (Figure 5.20). In this case, petroleum use is 35 percent lower than the 2005 level in 2030 and 73 percent lower in 2050. GHG emissions are 31 and 63 percent below the 2005 level in 2030 and 2050, respectively. If the AEO 2011 reference grid assumptions are used, the GHG reductions are 31 percent in 2030 and 56 percent in 2050.

Despite the cost of vehicle subsidies (over $50 billion present value) this scenario still has a substantial positive net present value of over $500 billion. Most of the benefits (about 50 percent) are due to uncounted energy savings from PEVs, which have substantially lower energy costs than ICEVs or HEVs (Figure 5.21).

Adding greater volumes of advanced biofuels (45 billion gge in 2050) to the PEV Transition Policy case reduces petroleum use relative to 2005 by 40 percent in 2030 and 94 percent in 2050. The GHG reductions in those years are estimated to be 34 and 75 percent assuming electricity generated by a low-carbon grid.

As described above, the initial costs for PEVs are substantially higher than for other technologies, primarily due to battery costs. If subsidies are not applied until battery costs have come down significantly, there is still opportunity for significant benefits. If the current advanced vehicle tax credits are allowed to expire in 2020, it is possible to induce a transition

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[12] It is likely that the feebates alone would induce manufacturers to realize fuel economy and emissions improvements similar to those assumed to result from standards, but that possibility has not been tested here (Greene et al., 2005).

[13] These estimated total subsidies may appear too high given a federal tax credit of only $7,500 for BEVs and $5,000 for PHEV-30s. However, states also offer incentives of up to $7,500, and manufacturers are very likely also subsidizing initial sales, partly to induce market success and partly to gain credits under the CAFE regulations and ZEV mandates.

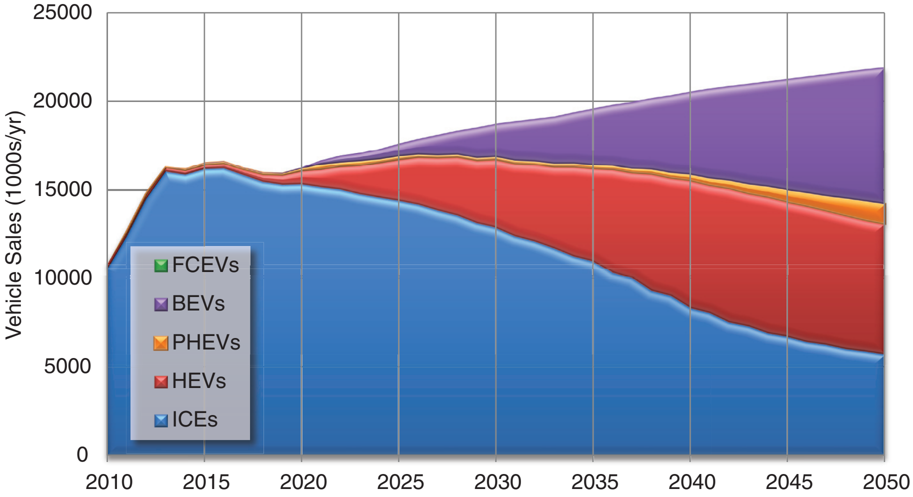

FIGURE 5.20 Vehicle sales by vehicle technology assuming midrange technologies and plug-in electric vehicle subsidies and additional incentives.

to PEVs by 2050 while waiting to apply technology-specific subsidies to PEVs until 2023. These subsidies are complemented by the usual IHUF and feebates. In this case, the total subsidy to BEVs is $13,000 per passenger car in 2023. However, it is reduced to $6,000 per vehicle by 2028, and by 2034 only the feebate remains. A similar subsidy trajectory is followed for PHEVs but is delayed by 6 years, beginning instead in 2029 after vehicle costs have been further reduced. By 2050, BEVs make up 35 percent of new-vehicle sales, while PHEVs are 6 percent, both shares similar to the cases above. Likewise, petroleum usage in 2030 is reduced by 34 percent, and petroleum usage and GHG emissions in 2050 are reduced by 73 and 63 percent, respectively, compared to 2005 levels; these are almost identical to the PEV transition case without biofuels but with the low-carbon grid, discussed above. The net present value is nearly identical ($520 billion compared to $540 billion), and the total cost of the subsidies necessary to produce the transition are essentially the same, as well, $50 billion.

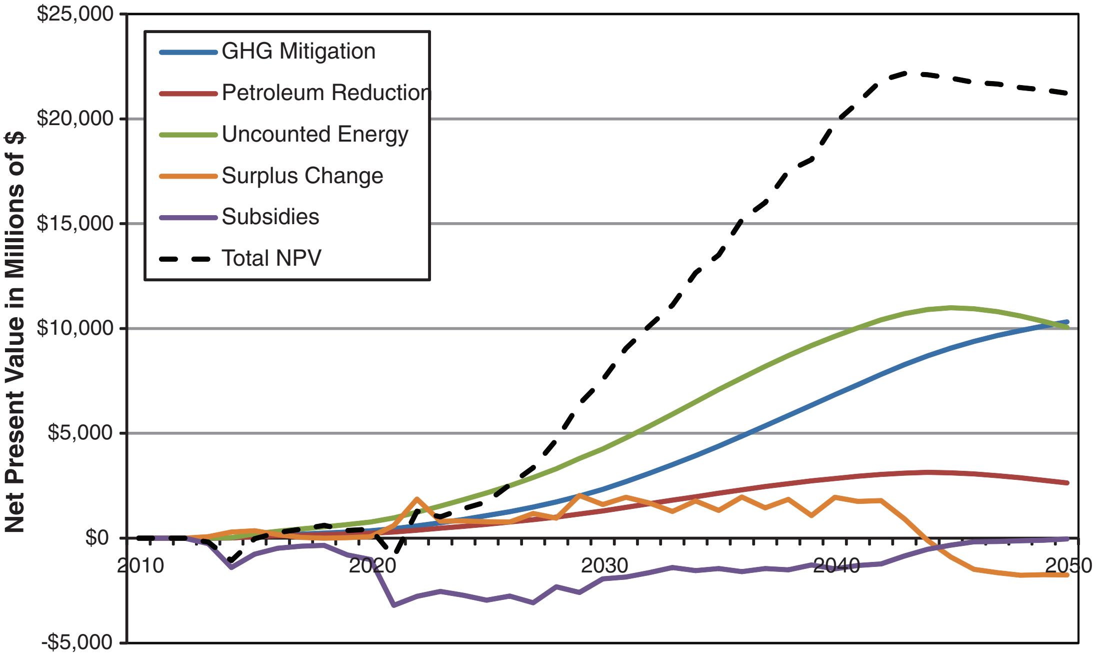

FIGURE 5.21 Estimated costs and benefits of the transition to 25 percent plug-in electric vehicles (PEVs) assuming midrange technologies and PEV subsidies and additional incentives.

5.4.6 Hydrogen Fuel Cell Electric Vehicle Cases

Given the midrange technology assumptions, if no early hydrogen infrastructure is provided and the existing tax credits are allowed to expire in 2020, a transition to FCEVs does not occur. An early transition to hydrogen fuel cell vehicles can be induced by ensuring that an adequate amount of hydrogen refueling infrastructure to support early vehicle sales is in place at least in some regions ahead of vehicle sales and that vehicle subsidies or mandates support early sales. All the FCEV transition cases include feebates reflecting social willingness to pay for GHG and oil reduction and the IHUF. The three carbon-intensity cases described in Chapter 3 were tested, beginning with low-cost hydrogen produced mainly by steam methane reforming without carbon capture and storage.

The first FCEV transition case assumes that 200 subsidized or mandated hydrogen refueling stations are put in place in 2014, 200 in 2015, and 100 more in 2016. These stations are likely to be geographically clustered, for example, in California and other states where ZEV requirements and other supporting policies are in place. Increased hydrogen vehicle subsidies (or mandates inducing implicit subsidies) begin in 2015 at $17,500 per vehicle (including the existing tax credit). The initial, high subsidies decline gradually to $16,000 per vehicle in 2020 and $6,000 by 2025. This induces modest levels of FCEV sales: 9,000 in 2015, followed by annual sales of 16,000, 21,000, and 26,000 in 2016-2018 (Figure 5.22). The transitional vehicle subsidy is ended in 2027, but the feebate system that in 2027 provides a $1,400 rebate for FCEVs and imposes a $500 tax on ICEVs remains in effect. By 2050, almost half of the vehicles on the road are FCEVs or HEVs.

In the low-cost hydrogen case, petroleum consumption is estimated to be 41 percent below the 2005 level in 2030. In 2050 petroleum consumption is down an estimated 90 percent relative to 2005 and GHG emissions are 59 percent lower. Assuming CCS is used in the production of hydrogen, greenhouse gas emissions are estimated to be 74 percent lower in 2050 and petroleum use is 95 percent below the 2005 level (Figure 5.23). Using assumptions to produce hydrogen with the lowest GHG impacts, 2050 GHG emissions are estimated to be 80 percent lower than in 2005, and petroleum use 96 percent below the 2005 level. Petroleum use in 2030 is estimated to be 42 percent below 2005 in this case. With the feebates in place, the higher-cost but lower-GHG-impact hydrogen increases FCEV sales: in the low-carbon production case FCEVs take an estimated 57 percent of the market in 2050, and in the low-cost production hydrogen case they capture 48 percent.

Despite the initial cost of subsidies that reach $6 billion per year in the mid-2020s, the estimated net present value of the policy-induced transition to hydrogen FCEVs is on the order of $1 trillion (Figure 5.24). The benefits are roughly equally composed of social benefits (GHG and petroleum reduction) and private benefits (fuel savings and consumers' surplus gains).

Adding advanced biofuels to the FCEV policy case reduces the 2050 market share of FCEVs from 57 to 46 percent. Low-GHG gasoline reduces the cost penalty that feebates levy on ICEVs; vehicles consuming drop-in biofuel instead of petroleum gasoline become more cost-competitive with FCEVs and gain market share. This is an illustration of how policies may interact in ways that make the combined impact smaller than the sum of the individual effects. Still, total petroleum use and GHG emissions are lower. In 2030, petroleum use is estimated to be 46 percent below the 2005 level and GHG emissions are 37 percent below (versus 42 and 35 percent, respectively, without advanced biofuels). In 2050, adding advanced biofuels reduces GHG emissions to 86 percent below the 2005 level and petroleum use to 100 percent below.

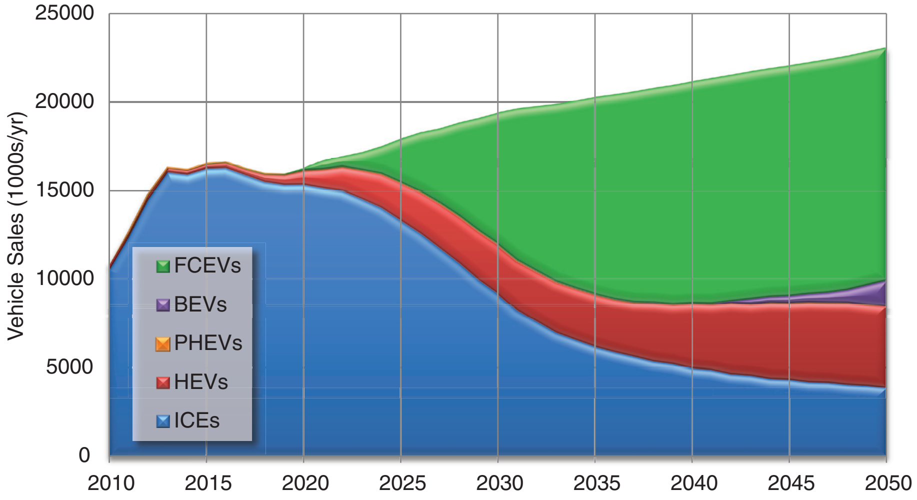

FIGURE 5.22 Vehicle sales by vehicle technology with midrange technology assumptions and low-carbon production of hydrogen, fuel cell vehicle subsidies, and additional incentives.

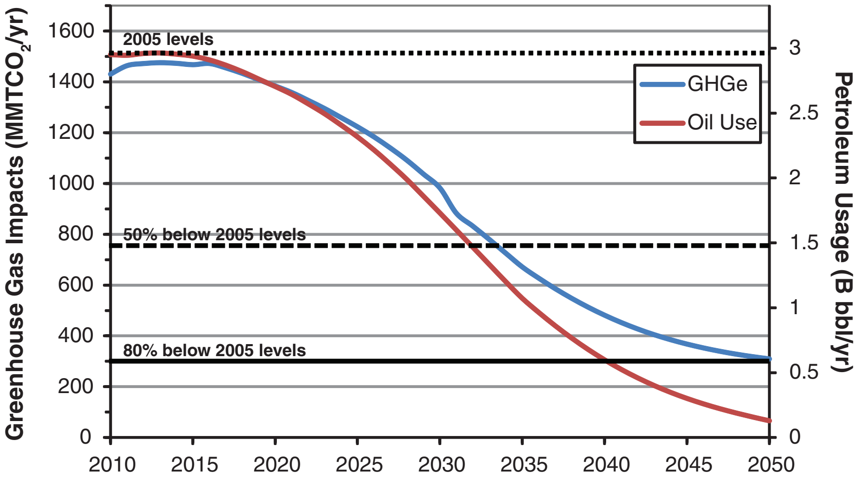

FIGURE 5.23 Changes in petroleum use and greenhouse gas (GHG) emissions with midrange technology assumptions, fuel cell vehicle subsidies and additional incentives, and a low-GHG infrastructure for the production of hydrogen.

5.4.7 Compressed Natural Gas Vehicles

Due to limitations of the LAVE model, CNGVs take the place of FCEVs; FCEVs are excluded from analyses in which CNGVs are included. Like FCEVs, only one type of CNGV is considered, CNG non-hybrid ICEVs. CNGVs have some advantages relative to other advanced technologies. Natural gas prices are lower than petroleum, biofuel, or hydrogen prices, and the infrastructure for natural gas production and distribution is nearly ubiquitous. This means that, unlike hydrogen, there is no initial phase of high prices at low volumes. Natural gas refueling stations are still required, however, and natural gas vehicles have lower range than gasoline vehicles due to the lower energy density of CNG.

The CNG policy case includes feebates and the IHUF, both commencing in 2015. Also in that year there is a transitional subsidy/mandate of $10,000 per CNGV. Like the vehicle subsidies in other cases, this could be borne by the manufacturer or government or shared between the two. The transitional subsidy is reduced each year and ended by 2025. In addition, 100 subsidized refueling stations are opened in 2014, 200 in 2015, and 100 more in 2016. CNGV sales peak at 49 percent from 2031-2034, then decline to 33 percent in

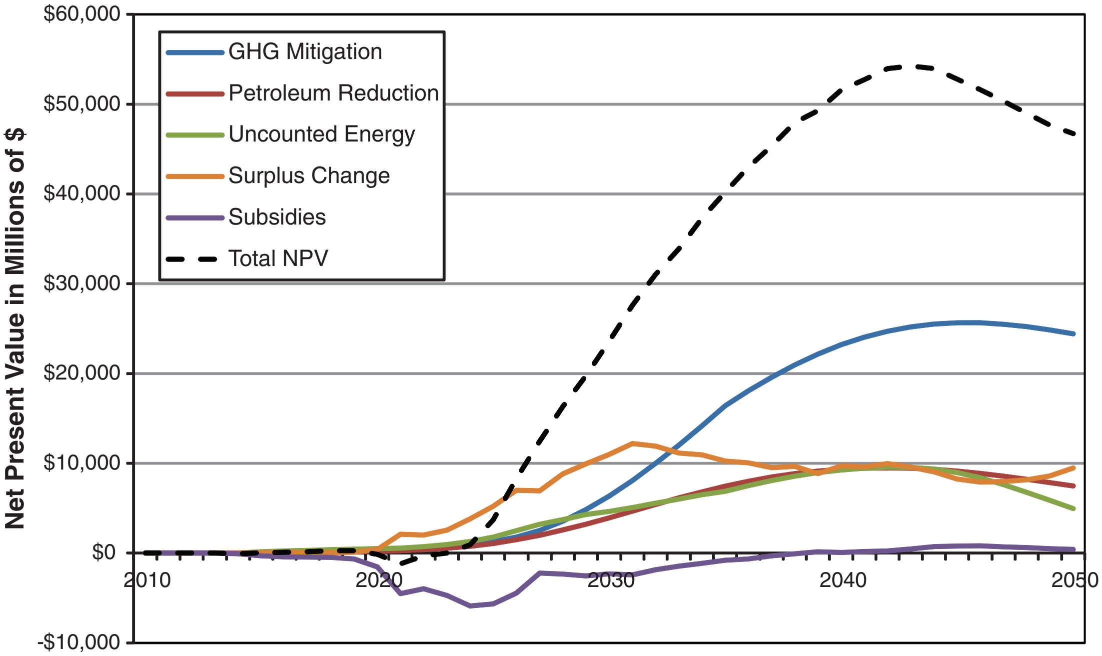

FIGURE 5.24 Present value cost and benefits of a transition to hydrogen fuel cell vehicles using midrange technology assumptions, fuel cell vehicle subsidies and additional incentives, and a low-GHG infrastructure for the production of hydrogen.

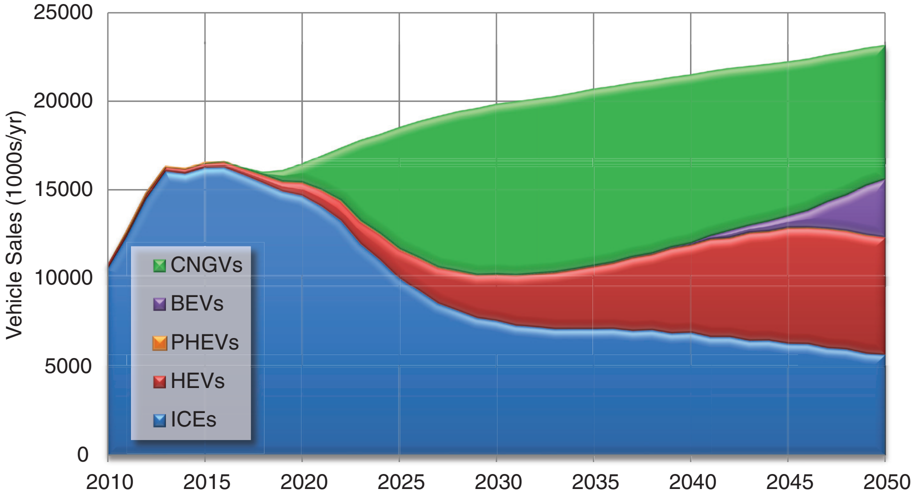

FIGURE 5.25 Vehicle sales by vehicle technology for midrange technology estimates and policies promoting compressed natural gas vehicles.

2050 (Figure 5.25), chiefly due to the feebates which favor BEVs and even HEVs and ICEVs over CNGVs.

In the CNG transition policy case, petroleum consumption is estimated to be 52 percent below the 2005 level in 2030. GHG emissions are 28 percent lower. In 2050, estimated petroleum use and GHG emissions are, respectively, 86 and 47 percent lower than 2005 levels (Figure 5.26). Adding advanced biofuels to the CNG transition case eliminates petroleum use in 2050 and reduces GHG emissions to an estimated 62 percent below the 2005 level. If it is assumed that some CNGVs will be hybrid vehicles, the model would suggest no more than a few additional percent reductions in GHG emissions because these CNG HEVs would not be further displacing gasoline-powered vehicles but rather less efficient CNG ICEVs. All greenhouse gas emissions for natural gas vehicles are strongly predicated on the methane leakage rates outlined in Chapter 3 due to methane's large global warming potential.

5.4.8 Plug-in Electric Vehicles and Hydrogen Fuel Cell Electric Vehicles

Combining subsidies to PEVs and FCEVs with advanced biofuels and also including the usual feebates and IHUF on energy eliminates petroleum use in 2050 and reduces GHG emissions by 88 percent versus 2005 levels. In 2030, a 56 percent reduction in petroleum use is achieved. The implied subsidies required to achieve this result are substantial. In 2015, a BEV gets a total subsidy of $20,500; a FCEV, $27,500; and a PHEV, $13,000. The implied subsidies decrease to about $3,000 per BEV and FCEV and half of that for PHEVs in 2025, including feebates. After

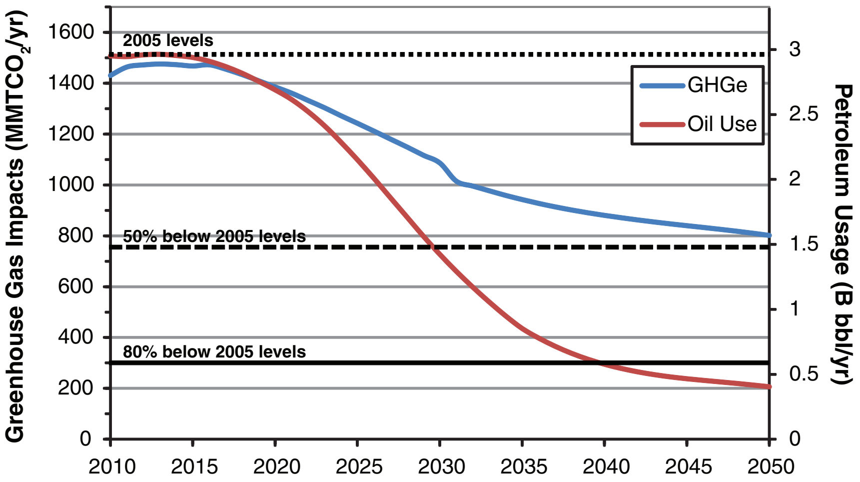

FIGURE 5.26 Changes in petroleum use and greenhouse gas emissions for midrange technology estimates with policies promoting compressed natural gas vehicles.

2030 the transitional subsidies are ended but the feebates remain. The total NPV of subsidies is approximately $140 billion. Although both technologies attain sustainable market shares, they compete with one another as well as with ICEVs and HEVs, which reduces their combined impact (Figure 5.27). The presence of several competing technologies in the marketplace tends to limit diversity of choice (fewer makes and models for any given technology) and to a lesser extent reduces fuel availability (due to fewer vehicles of any one type on the road), in comparison to a case dominated by one or two technologies. Nonetheless, this case achieves a NPV gain of $1.7 trillion versus the same technology assumptions without policy interventions to induce transitions. In this case, all of the liquid fuel used by vehicles with internal combustion engines is biofuel. In addition, the grid is low-carbon, as is hydrogen production. As a result, by 2050, there is almost no difference in the social costs (GHGs and petroleum use) of the different powertrain technologies. No vehicle receives a fee or a rebate that exceeds $50.

5.4.9 Optimistic Technology Scenarios

Optimistic technology scenarios imply breakthrough advancement of a given technology. These are taken to represent roughly a 20 percent likelihood occurrence in technological development for the respective technology. Such advancement is less likely than the midrange assumptions, although if it occurs, it changes the landscape for adoption of a technology, both in its costs and its benefits. In brief, the optimistic technology cases show that better-than-anticipated progress for plug-in vehicle technology combined with a decarbonized grid and assuming the same policies spelled out for the midrange cases above could come close to achieving the GHG and petroleum reduction goals by 2050 but fall short of the 2030 petroleum use goal. A parallel case for fuel cell vehicles could achieve or exceed all of the goals. A full explanation of the optimistic cases is contained in Section H.4 in Appendix H.

5.4.10 Summary of Policy Modeling Results

The results of all the cases are summarized and compared in Tables 5.3 and 5.4 and in Figures 5.28 and 5.29. The fuel infrastructure investment costs modeled to achieve each scenario can be found in Section H.3 in Appendix H. The cases in Tables 5.3 and 5.4 are grouped in the same order as the case descriptions above. Abbreviations used in the table are explained in Table 5.5. For each group, there is a Base Case using the identical vehicle technology assumptions but without energy transition policies. All cases, including the Base Cases, assume policies requiring continued improvements in vehicle energy efficiencies and, therefore, all cases also include feebates consistent with the fuel economy and emissions standards. The inherent uncertainties in the model estimates should be kept in mind.

Only three cases are estimated to meet or exceed the 50 percent petroleum reduction goal in 2030 and the 80 percent petroleum and GHG reduction goals in 2050. One is based on optimistic assumptions for FCEV technology; the other two require both plug-in and hydrogen fuel cell market success, plus the low-carbon production of electricity and hydrogen, and the supporting policies of fuel economy/emissions standards and the IHUF on energy.

Two additional cases meet the 2030 petroleum goal but miss the 2050 GHG goal by wide margins. Both cases are based on a substantial transition to CNGVs, and such a transition may result in even more greenhouse gas emissions than modeled due to uncertainty in methane leakage rate and methane's substantial greenhouse warming potential. Eight cases are in the range of 40 to 50 percent petroleum reduction in 2030. Given the uncertainty inherent in the

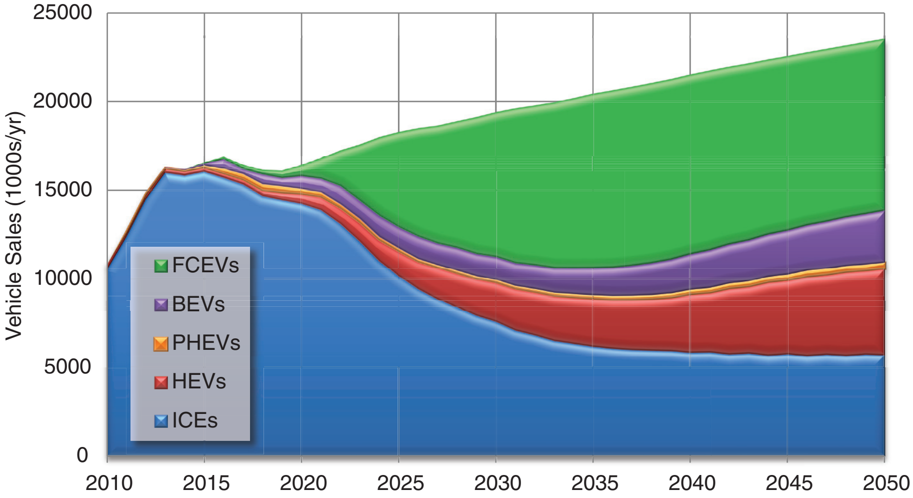

FIGURE 5.27 Vehicle sales by vehicle technology for midrange technologies and policies promoting the adoption and use of plug-in electric vehicles, hydrogen fuel cell electric vehicles, and biofuels.

TABLE 5.3 Summary of Estimated Petroleum and GHG Reductions in the Policy Cases

	Oil Reduction (% reduction below 2005 level)		GHG Reduction (% reduction below 2005 level)		Oil Consumption (billion bbl/yr) 2005 = 2.96		GHG Emissions (MMTCO$_2$e/yr) 2005 = 1514	
Scenario[a]	2030	2050	2030	2050	2030	2050	2030	2050
BAU	–5%	4%	–3%	9%	2.8	3.1	1,467	1,645
Reference	–29%	–27%	–26%	–22%	2.1	2.2	1,118	1,184
Eff+FBSC	–32%	–61%	–29%	–50%	2.0	1.2	1,082	755
Eff+FBSC+IHUF	–33%	–64%	–29%	–52%	2.0	1.1	1,071	721
Eff+Bio+FBSC+IHUF	–37%	–86%	–32%	–66%	1.9	0.4	1,030	508
Eff+Bio w/CCS+FBSC+IHUF	–37%	–86%	–35%	–78%	1.9	0.4	979	335
Eff+Intensive Pricing+LCe	–38%	–87%	–35%	–74%	1.8	0.4	990	389
PEV+ FBSC+IHUF+Trans+AEOe	–35%	–71%	–31%	–56%	1.9	0.9	1,049	662
PEV+ FBSC+IHUF+Trans+LCe	–35%	–73%	–31%	–63%	1.9	0.8	1,046	567
PEV(later)+FBSC+IHUF+Trans+LCe	–34%	–73%	–30%	–63%	2.0	0.8	1,055	563
PEV+Bio+FBSC+IHUF+Trans+LCe	–40%	–94%	–34%	–75%	1.8	0.2	1,005	381
FCEV+FBSC+IHUF+Trans+L\$H$_2$	–41%	–91%	–32%	–59%	1.7	0.3	1,025	621
FCEV+FBSC+IHUF+Trans+H$_2$CCS	–42%	–95%	–34%	–74%	1.7	0.1	993	391
FCEV+FBSC+IHUF+Trans+LCH$_2$	–42%	–96%	–35%	–80%	1.7	0.1	982	310
FCEV+Bio+FBSC+IHUF+Trans+LCH$_2$	–46%	–100%	–37%	–86%	1.6	0.0	949	209
CNGV+FBSC	–32%	–61%	–29%	–50%	2.0	1.2	1,082	755
CNGV+FBSC+IHUF+Trans	–52%	–86%	–28%	–47%	1.4	0.4	1,086	801
CNGV+Bio+FBSC+IHUF+Trans	–56%	–100%	–31%	–62%	1.3	0.0	1,045	568
Eff (Opt)+FBSC	–38%	–68%	–34%	–59%	1.8	0.9	1,000	620
Eff (Opt)+Bio+FBSC+IHUF	–43%	–95%	–37%	–76%	1.7	0.2	947	367
PEV (Opt)+FBSC+AEOe	–32%	–78%	–29%	–60%	2.0	0.7	1,082	607
PEV (Opt)+FBSC+IHUF+Trans+LCe	–35%	–89%	–31%	–76%	1.9	0.3	1,048	368
FCEV (Opt)+FBSC+L\$H$_2$	–32%	–61%	–29%	–50%	2.0	1.2	1,082	755
FCEV (Opt)+FBSC+IHUF+Trans+LCH$_2$	–50%	–100%	–41%	–90%	1.5	0.0	888	150
PEV+FCEV+FBSC+IHUF+Trans+LCe+LCH$_2$	–52%	–99%	–42%	–82%	1.4	0.0	872	267
PEV+FCEV+Bio+FBSC+IHUF+Trans+LCe+LCH$_2$	–56%	–100%	–45%	–87%	1.3	0.0	839	190

[a] Base Cases are indicated in boldface. Eff+FBSC serves as a Base Case for the four groups below it: Eff, Intensive Pricing, PEV, and FCEV, as well as for the mixed cases in the final grouping including both PEVs and FCEVs. See Table 5.5 for explanation of scenario components.

modeling analysis, that may be close enough. All of these cases meet the 2050 petroleum reduction goal. Six of the eight cases achieving an estimated 40 percent or greater reduction in petroleum use by 2030 also achieve a 70 percent or greater reduction in GHG emissions by 2050. Three are based on hydrogen fuel cell market success; one combines plug-in vehicle market success with biofuels. One relies on efficiency plus greater use of pricing policies, but this also induces a massive shift to plug-in vehicles by 2050. The final case combines optimistic efficiency improvements with biofuels to achieve an estimated 76 percent reduction in GHG emissions in 2050.

All five cases that meet the 2050 GHG reduction goal also imply near elimination of petroleum use. This is likely to be more difficult than the modeling analysis makes it appear. Near elimination of U.S. petroleum use, if it is also accomplished by other petroleum using countries, would cause world petroleum prices to fall. Falling petroleum prices have not been included in the modeling analysis but would make it more difficult for alternative technologies to succeed. This effect could be countered by a policy setting a price floor on petroleum, as discussed in Chapter 6.

As uncertain as these estimates are, they provide several important insights. First, reaching the 2030 and 2050 goals will be difficult. It will require strong and sustained policies to continuously improve the energy efficiency of LDVs and to de-carbonize the systems supplying energy for the vehicles, and very likely it will also require strong policies to induce a transition to one or more of the advanced power-train technologies. Second, continued improvement in vehicle and fuel technologies is essential. Although the committee considers the technological progress assumed in the committee's scenarios to be reasonably likely, it is not guaranteed. Given that several technological advances are necessary to come close to meeting the goals, research and development of all the technologies considered in this report is a high priority.

If the alternative technologies develop and are deployed according to the committee's technological and market assumptions, the scenario modeling indicates that the additional costs of any transition may be much smaller

TABLE 5.4 Total Net Present Value in 2050 for Various Cases

	Net Present Value (billions $)					
Scenario[a]	Surplus Change	Subsidies	GHG Mitigation	Petroleum Reduction	Uncounted Energy	Total NPV
BAU	0.0	0.0	0.0	0.0	0.0	0.0
Reference	0.0	0.0	0.0	0.0	0.0	0.0
Eff+FBSC	0.0	0.0	0.0	0.0	0.0	0.0
Eff+FBSC+IHUF	–7.0	–0.8	44.6	16.6	78.2	131.7
Eff+Bio+FBSC+IHUF	–20.0	4.8	285.6	151.0	49.0	470.3
Eff+Bio w/CCS+FBSC+IHUF	–40.7	6.5	507.8	150.5	48.0	672.2
Eff+Intensive Pricing+LCe	–361.3	–128.0	520.1	253.4	1103.4	1387.5
PEV+ FBSC+IHUF+Trans+AEOe	43.0	–53.3	136.3	72.6	285.5	484.2
PEV+ FBSC+IHUF+Trans+LCe	23.8	–52.3	218.9	76.6	273.8	540.7
PEV(later)+FBSC+IHUF+Trans+LCe	29.2	–50.6	212.6	72.3	259.6	523.2
PEV+Bio+FBSC+IHUF+Trans+LCe	24.7	–45.7	437.1	205.6	226.8	848.6
FCEV+FBSC+IHUF+Trans+L$\$H_2$	307.0	–38.6	210.3	200.4	287.0	965.9
FCEV+FBSC+IHUF+Trans+H_2CCS	279.7	–44.0	493.0	222.6	289.0	1240.3
FCEV+FBSC+IHUF+Trans+LCH_2	252.9	–45.7	591.2	225.3	198.0	1221.7
FCEV+Bio+FBSC+IHUF+Trans+LCH_2	276.2	–38.5	725.1	275.4	56.9	1295.1
CNGV+FBSC	0.0	0.0	0.0	0.0	0.0	0.0
CNGV+FBSC+IHUF+Trans	414.3	–32.7	–40.1	248.1	251.1	840.7
CNGV+Bio+FBSC+IHUF+Trans	396.0	–31.1	222.4	346.9	210.6	1144.7
Eff (Opt)+FBSC	0.0	0.0	0.0	0.0	0.0	0.0
Eff (Opt)+Bio+FBSC+IHUF	–20.1	2.5	291.7	153.5	60.2	487.8
PEV (Opt)+FBSC+AEOe	0.0	0.0	0.0	0.0	0.0	0.0
PEV (Opt)+FBSC+IHUF+Trans+LCe	18.0	–54.1	280.7	79.2	299.6	623.4
FCEV (Opt)+FBSC+L$\$H_2$	0.0	0.0	0.0	0.0	0.0	0.0
FCEV (Opt)+FBSC+IHUF+Trans+LCH_2	596.0	–47.0	869.4	294.2	590.3	2302.9
PEV+FCEV+FBSC+IHUF+Trans+LCe+LCH_2	345.0	–145.3	739.8	300.8	442.0	1682.3
PEV+FCEV+Bio+FBSC+IHUF+Trans+LCe+LCH_2	371.7	–137.4	855.8	340.6	264.8	1695.5

[a] Base Cases are indicated in boldface. Eff+FBSC serves as a Base Case for the four groups below it: Eff, Intensive Pricing, PEV, and FCEV, as well as for the mixed cases in the final grouping including both PEVs and FCEVs. See Table 5.5 for explanation of scenario components.

than the sum of private and public benefits. The benefits considered in the model include both public and private benefits such as benefits to the owners of the vehicles (i.e., the uncounted energy savings), benefits to the owners of all vehicles (i.e., the increased consumer surplus), and benefits to society at large (the benefits of GHG emissions reduction and reduced petroleum use). Costs refer to the additional costs of the transition over and above what the market is willing to do voluntarily, as represented by the respective Base Case. These include any increases in vehicle or fuel costs not included in consumers' surplus, net subsidies, and consumers' surplus losses. If there were increases in GHG emissions or petroleum use, these would also be included in transition costs.

5.5 COMPARISON TO PREVIOUS WORK

The LAVE-Trans modeling represents a significant step toward more completely modeling scenarios by which the LDV fleet could be drastically changed. However, because of the uncertainties concerning the behavior of consumers and firms that underpins these modeling results as well as the uncertainty in projected costs and available technologies, it is important to consider these results in the context of the large body of literature on transitions to alternative vehicles and fuels. Here the focus is on some of the key findings and assumptions of the modeling compared to the available literature; a detailed summary of key reports on the matter is given in Appendix D.

A number of policy scenarios modeled above include the use of a large volume of biofuels (up to 45 billion gge/yr) in order to meet the goals for petroleum reduction and/or GHG emissions reductions from the LDV fleet. As is described in Chapter 3, the biomass required for such volumes of cellulosic drop-in fuel is plausible; many previous studies indicate a similar level of available biomass resource (UCD, 2011; NRC, 2008, 2009b; DOE, 2011; Greene and Plotkin, 2011; Pacala and Socolow, 2004). However, there is still uncertainty about the levels of production necessary to contribute significantly to the fueling of the LDV fleet due to the unknown future cost of fuels produced from biomass relative to gasoline produced from petroleum (DOE, 2011).

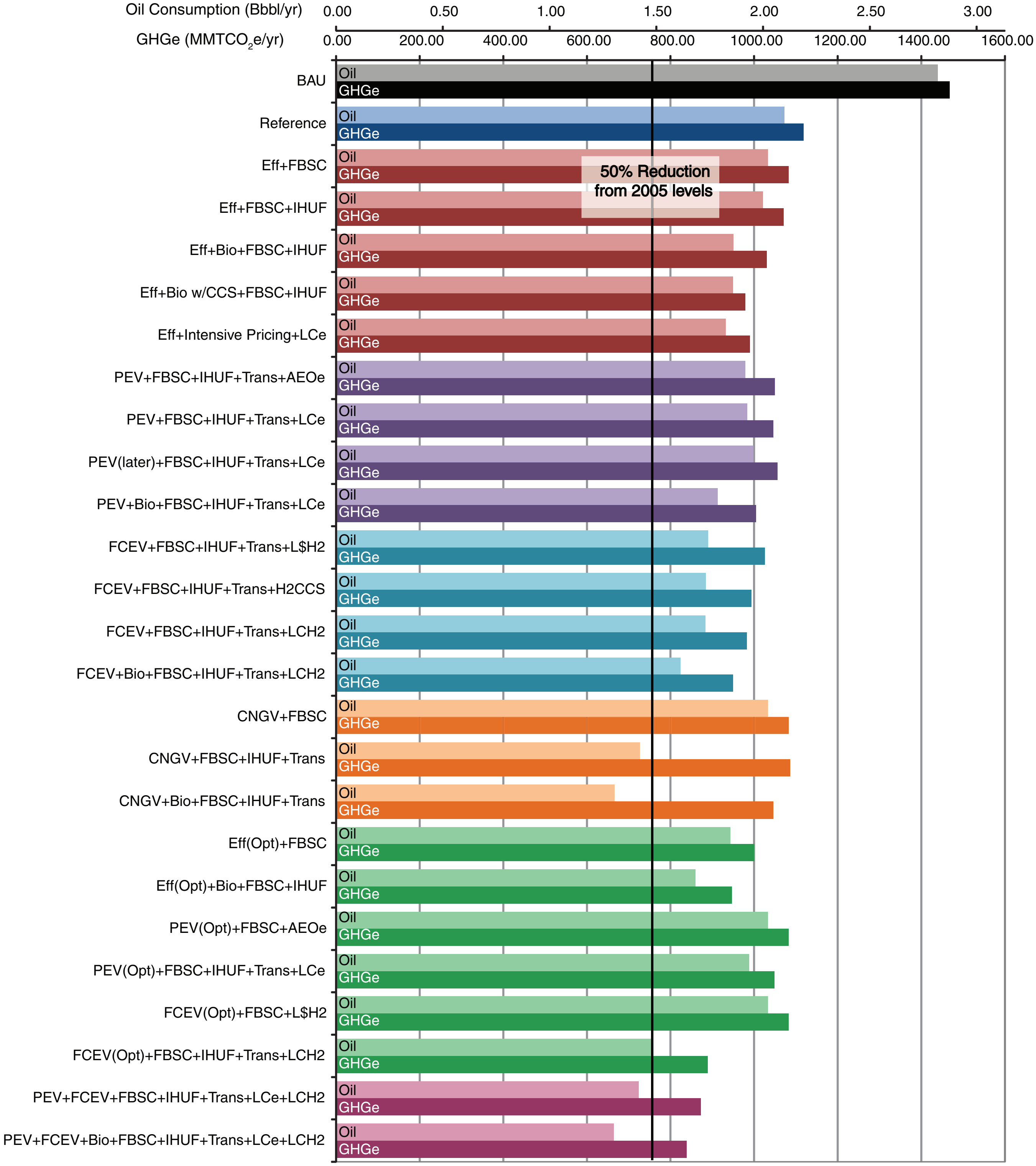

FIGURE 5.28 Estimated petroleum usage and greenhouse gas emissions in 2030, by policy scenario. Hydrogen fuel cell electric vehicle (FCEV) and plug-in electric vehicle (PEV) scenarios utilize Low-Carbon production of alternative fuel unless otherwise specified. See Table 5.5 for explanation of scenario components.

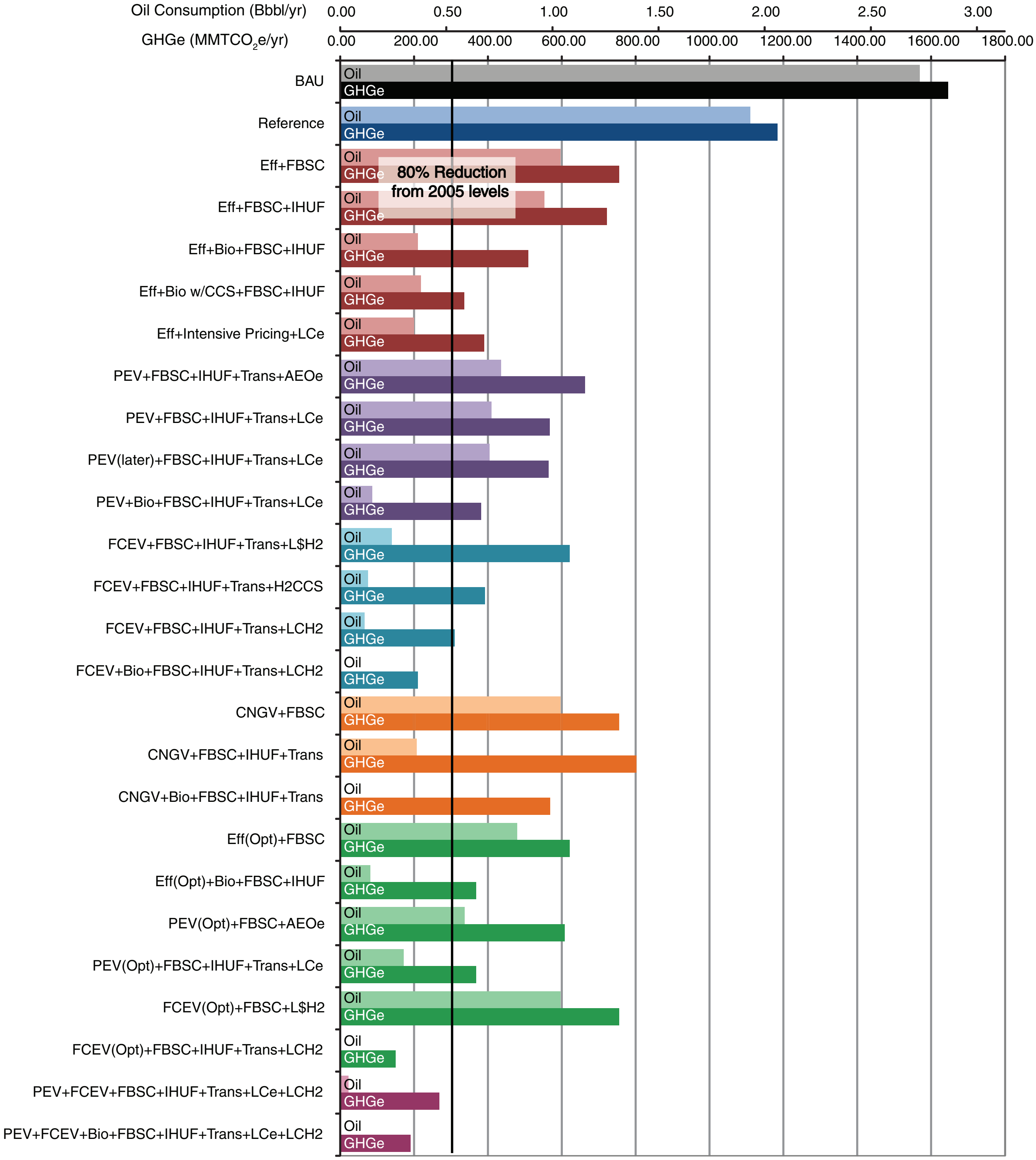

FIGURE 5.29 Estimated petroleum usage and greenhouse gas emissions in 2050, by policy scenario. Hydrogen fuel cell electric vehicle (FCEV) and plug-in electric vehicle (PEV) scenarios utilize Low-Carbon production of alternative fuel unless otherwise specified. See Table 5.5 for explanation of scenario components.

TABLE 5.5 Abbreviations for Policies Considered in the LAVE-Trans Model

Eff	Improved vehicle efficiency—midrange technology assumptions
FBSC	Feebates based on societal willingness to pay for GHG and petroleum reduction
IHUF	User fee on energy indexed to the average energy efficiency of all on-road vehicles
Bio	Assumes increased use of thermochemical biofuels up to 45 billion gge in 2050
CCS	Includes the use of carbon capture and storage
Intensive pricing	Includes IHUF, FBSC, carbon/oil tax, and feebates based on fuel savings (see Sections 5.4.2 and 5.4.4)
Trans	Transition policies consisting of vehicle and fuel infrastructure subsidies or mandates
AEOe	Reference Case electricity grid based on *Annual Energy Outlook 2011*
LCe	Low-Carbon electricity grid
LH_2	Low-Cost production of hydrogen
H_2CCS	Production of hydrogen with Carbon Capture and Storage
LCH_2	Low-Carbon production of hydrogen
(Opt)	Optimistic technology assumptions for the indicated technology (see Section H.4 in Appendix H for details)

NOTE: For more details on fuels production, see Table 5.1 and Chapter 3. Vehicle technology assumptions are described in Chapter 2. Policies are defined in Box 5.2.

A further limit on the availability of biofuels is likely to be competition from other uses, such as in aircraft or heavy-duty vehicles (UCD, 2011). Such limited availability would prevent achievement of an 80 percent reduction in GHG emissions without advanced progress in hydrogen fuel cell technology. A UC-Davis report noted that biofuels would play a pivotal role in any policy scenario designed to reduce GHG emissions from the transportation sector, particularly in the next two decades while deployment of advanced powertrain vehicles is still in its infancy (Yeh et al., 2008). The committee accepted as a premise in its modeling the achievement by 2030 of the production of volumes of biofuel specified in RFS2 and did not examine scenarios in which biofuel deployment did not achieve these levels.

As can be seen from the midrange cases in Figure 5.29, improvements in vehicle efficiency, particularly when combined with policies to drive consumers to purchase efficient vehicles, offer the possibility of large reductions in petroleum consumption and GHG emissions. These improvements in efficiency are dependent on the availability of the highly efficient vehicles described in Chapter 2. Based on the CAFE standards out to model year 2025 (EPA and NHTSA, 2011) as well as a number of studies looking out the next 20 years or more (ANL, 2011; DOT, 2010; UCD, 2011; NRC, 2010a,b; Bandivadekar et al., 2008; Bastani et al., 2012), the committee's assessment of potential fuel consumption reductions in the near-future (to 2030) are largely in line with much of this literature, particularly given the committee's charge to assess the *potential* for future improvements. However, there is substantial uncertainty about vehicle efficiencies out to 2050. The committee chose to attack this problem of uncertainty by directly addressing the potential for reducing the losses in the vehicles' powertrains without prescribing particular technological solutions. It is worth noting that some of the technologies likely to be applied over the next few years (e.g., cooled exhaust gas recirculation) were not known to be viable 10 years ago, and continued improvement in materials and design has enabled load reductions in areas such as tire rolling resistance and weight reduction beyond what many would have thought practical just a decade or so ago. Although some of the known technologies may not pan out as planned, it is also plausible that there will be improvements beyond what is now known. The committee's analysis of the potential for technological improvement to LDVs has tried to balance these judgment issues. Based on these assumptions, the committee's projections for 2050 exceed those of many prior studies, particularly those that relied upon full-system simulation (UCD, 2011; ANL, 2009, 2011). Studies that are less optimistic about the possibility of significant load reductions yield little improvement in fuel consumption between the mid-term (2030) and long-term (2050) (DOT, 2010; NRC, 2010a, 2010b; EPRI and NRDC, 2007). If the committee's assessment of the long-term potential for highly efficient vehicles is proved incorrect, this will significantly hamper the effectiveness of all scenarios to reduce petroleum consumption and GHG emissions, since all alternative vehicles share the same basic load reductions enabling their high efficiencies. Recent efforts by Bastani et al. (2012) attempt to describe the most likely trajectory of the LDV fleet and show precisely this. Notably, the resultant *likely* efficiencies are far less than the committee's own assertions, as might be expected. Furthermore, this work shows the significance of meeting future fuel economy standards. As noted in the committee's own work, fuel economy standards will have to be an important driver in reducing vehicle energy consumption.

One of the major implications of the committee's modeling results is the difficulty in attaining the goals for reductions in GHG emissions and petroleum consumption chiefly through a transition to PEVs. The limited utility of BEVs and the higher costs of PHEVs remain a significant barrier in any scenario. The committee's assumptions on costs, however, agree with the majority of the literature on the topic; each report indicated a lower long-run cost for FCEVs and substantially elevated costs for both BEVs and long-range PHEVs (30+ mile all-electric range) (DOT, 2010; UCD, 2011; NRC, 2010a, 2010b; ANL, 2011). PHEVs with a lower range do show reduced cost barriers because of their smaller batteries, but they also offer significantly less potential for fuel displacement and reduced GHG emissions. Furthermore, as electricity prices increase over time with the increasingly clean electric grid and gasoline use by comparable ICE and hybrid vehicles decreases, the price advantage of fuel/electricity consumption of a BEV or a PHEV diminishes. These are factors not considered in any of the other reports on the transition to alternatively fueled LDVs.

Ultimately, the committee found numerous pathways to attain significant reductions in GHG emissions and petroleum consumption. The levels of GHG reductions are of similar magnitude to those described in previous studies (Figure 5.30); however, the specifics of the pathways themselves are often very different. For example, although the proposed UC-Davis scenarios for LDV GHG emissions reductions appear to be of a comparable magnitude, a large fraction of the reductions in the scenarios with the lowest GHG emissions come from a 25 percent decrease in VMT per capita, resulting in a 324 $MMTCO_2$ decrease in emissions from LDV transportation. There is also a notable difference in the Davis results for the FCEV scenario. Here, McCollum and Yang (2009) have limited penetration of FCEVs to 60 percent of new-car sales, whereas the NRC modeling results show the potential for much greater penetration of FCEVs, spurred on both through low future costs and policy action. Figure 5.30 indicates a sizable disparity between the efficiency cases of the VISION and LAVE-Trans models and previous NRC studies (NRC, 2008; 2010a). This difference is primarily a result of the more optimistic vehicle efficiencies presumed in the current work. A similar disparity is seen in a comparison with results of the HyTrans model (Greene and Leiby, 2007), although fuel production pathways, market analysis, and policies applied in the HyTrans analysis also deviate from those used in the committee's work. Small differences between the VISION and LAVE-Trans models are also observed for reasons outlined in Section 5.4.1.

The committee's modeling results are generally consistent with the available literature in both assumptions and results; however, the LAVE-Trans model has allowed the committee to build on this previous body of work to examine the transition costs associated with a shift to alternative vehicles and fuels in the LDV fleet. Moreover, the committee has examined several different policy options for achieving this transition, including multiple carbon pricing options, feebates, fuel taxes, and vehicle subsidies, leading to a number of pathways exhibiting sizable reductions in petroleum consumption and greenhouse gas emissions.

5.6 ADAPTING POLICY TO CHANGES IN TECHNOLOGY

Uncertainty is inherent in policy making for a transition to vehicles fueled by energy sources with reduced carbon impacts. The future path of technological development is uncertain. Future market conditions are also uncertain; indeed many economists have concluded that gasoline prices over the past several decades are best predicted by a

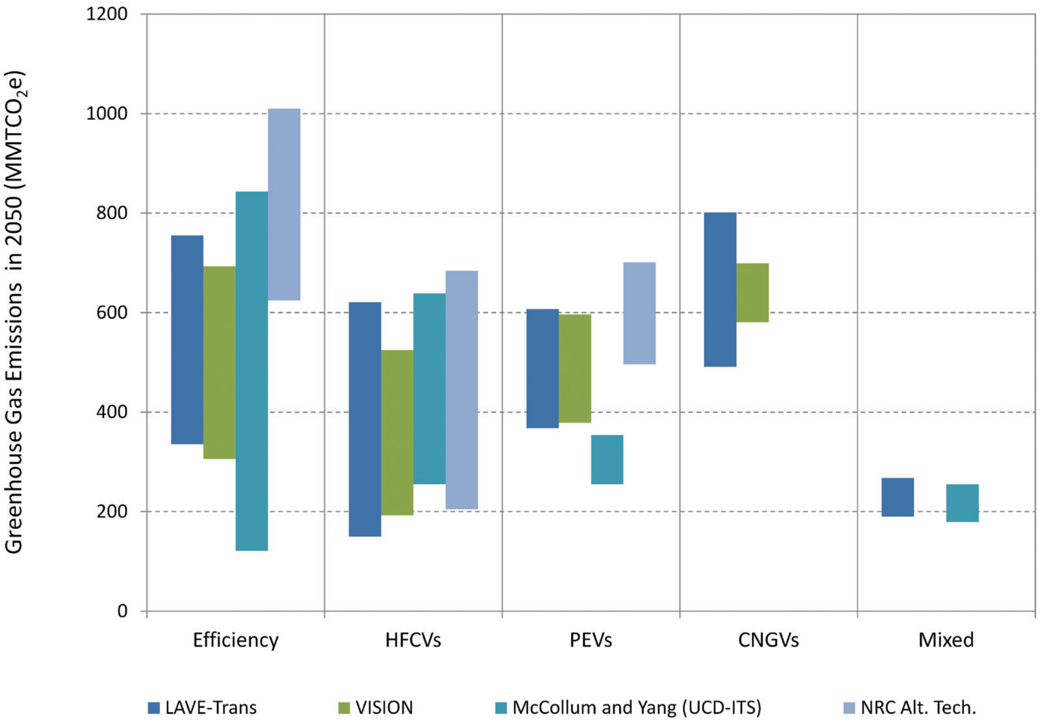

FIGURE 5.30 Comparison of greenhouse gas emissions scenarios.

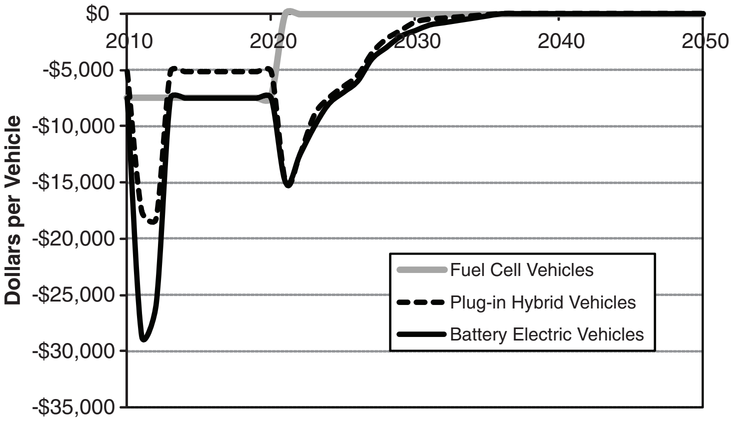

FIGURE 5.31 Assumed battery electric vehicle and plug-in hybrid electric vehicle subsidies in Optimistic EV Technology Scenario.

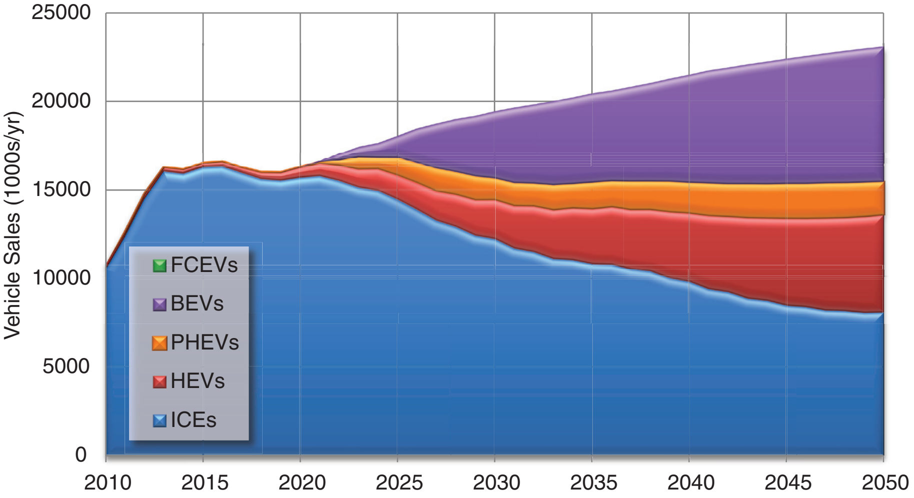

FIGURE 5.32 Vehicle sales by technology: Optimistic Plug-in Electric Vehicle Scenario.

random walk[14] (e.g., Hamilton, 2009; Anderson et al., 2011; Alquist et al., 2012). And as emphasized above, many of the parameters that drive the committee's modeling results are uncertain because knowledge of consumers' evaluation of limited-range vehicles, limited fuel availability, and other key factors is poor for present circumstances and worse for 30 to 40 years in the future. And, of course, the future will present opportunities and challenges that were not anticipated. In this section, the LAVE model is used to illustrate some of the challenges these uncertainties present to policy makers.

Policies that would work well if technologies advance as in the committee's midrange or optimistic cases may fail if technological progress stalls or is more expensive than anticipated. One technology may be expected to advance rapidly and yet a different technology turns out to exceed expectations. To illustrate these points, the LAVE model was used to construct three hypothetical scenarios. These scenarios are not predictions, nor do they reflect the committee's judgments about the likelihood of success of the technologies used to illustrate the role of uncertainty. The choice of technologies that succeed or fail in the scenarios below is arbitrary.

The first scenario includes a policy of subsidies for PHEVs and BEVs that works well assuming optimistic technological progress for these two technologies and midrange progress for all others. The scenario also assumes high biofuel intensity and low-carbon production of electricity and hydrogen. The vehicle subsidies for 2010-2012 were chosen to match actual sales of BEV and PHEV vehicles in the United States and include the federal tax credit of $7,500 per vehicle, as well as state subsidies and implicit subsidies by manufacturers introducing these vehicles. Only the federal subsidy is assumed to continue until 2020 and then end. In 2021 a new subsidy of $15,000 per vehicle is assumed for

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[14] A random walk is a mathematical formalism for a stochastic process defined as a series of random steps. In this case, oil prices are considered as a Gaussian random walk, meaning that the size of the step follows a Gaussian probability distribution.

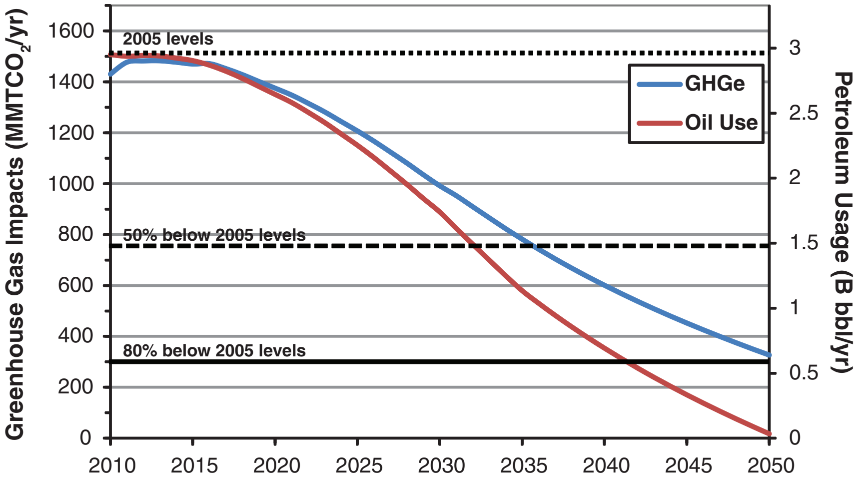

FIGURE 5.33 Changes in petroleum use and greenhouse gas emissions versus 2005: Optimistic Plug-in Electric Vehicle Scenario.

both vehicle types, decreasing each year until all subsidies are ended after 2035 (Figure 5.31).

The result is a successful, sustainable market penetration of PEVs. In 2050 BEVs attain a market share of 33 percent, PHEVs have an 8 percent share, and largely biofuel-powered HEVs and ICEVs claim 24 and 35 percent of the new-vehicle market, respectively (Figure 5.32).

The improvements in fuel economy, high penetration of drop-in biofuels (45 billion gallons in 2050), and market success of grid-connected vehicles powered by electricity produced by a low-carbon grid essentially eliminate oil use by LDVs and reduce GHG emissions by 78 percent, for all practical purposes meeting both 2050 goals. The 2030 goal is almost met by a 41 percent reduction in petroleum use versus the 2005 level (Figure 5.33).

The cost of subsidies to induce the transition is substantial, $130 billion NPV discounted to 2010 at 2.3 percent per year. The subsidies together with the lower energy costs of plug-in vehicles generate consumers' surplus benefits that exceed the subsidy costs (Figure 5.34). When uncounted energy savings over the full life of the vehicles and the societal values of reduced GHG emissions and oil use are added to the other costs and benefits, the NPV of the transition policies is over $600 billion. The subsidies must be paid before most of the benefits are received, however, putting a large amount of capital at risk.

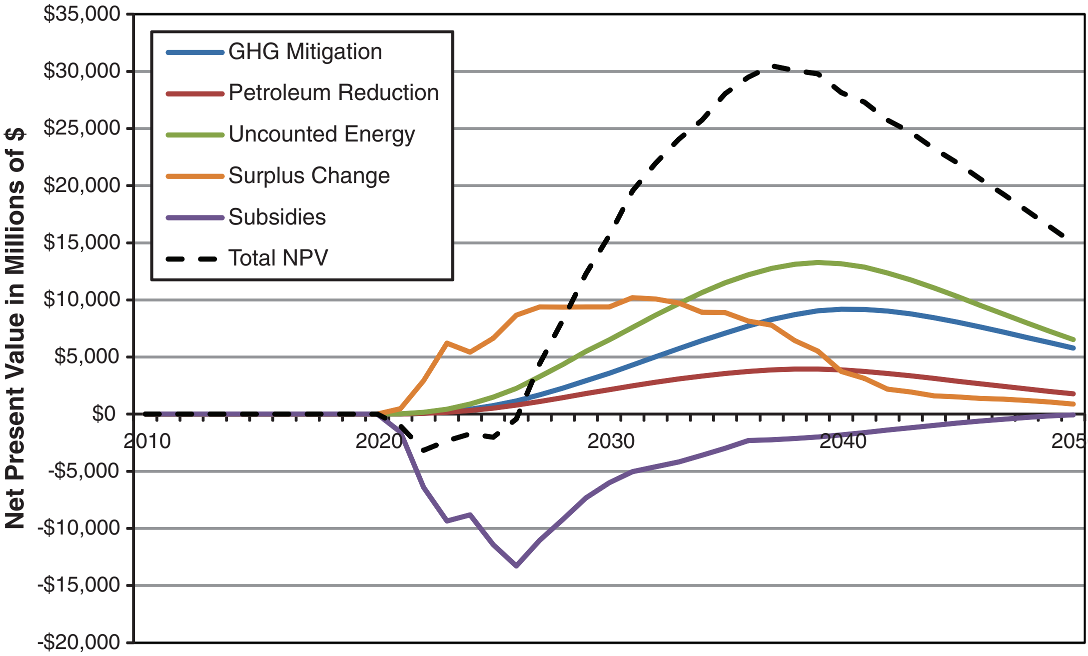

FIGURE 5.34 Net present value of the costs and benefits of the transition: Optimistic Plug-in Electric Vehicle Scenario.

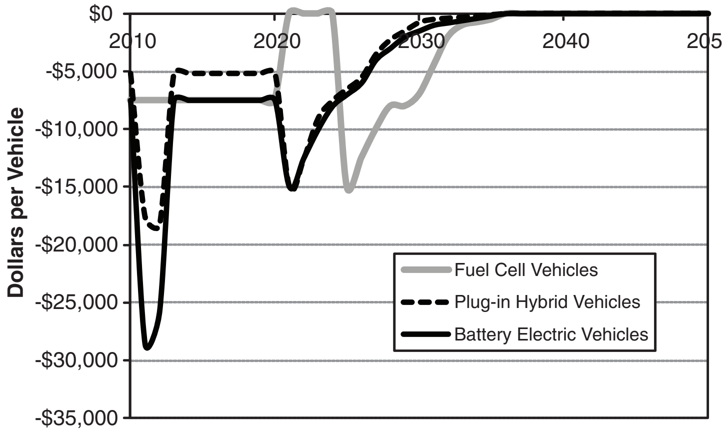

FIGURE 5.35 Assumed battery electric and plug-in hybrid electric vehicle subsidies in Pessimistic Plug-in Electric Vehicle Technology Scenario with Adaptation.

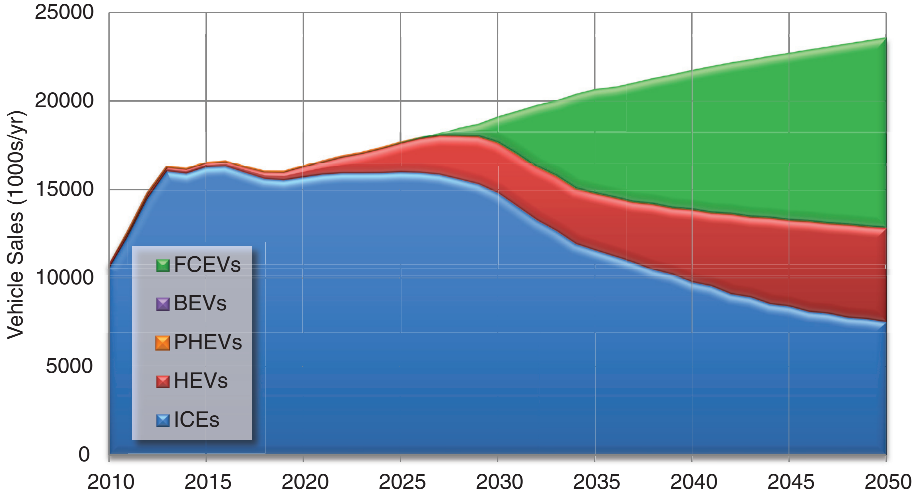

FIGURE 5.36 Vehicle sales by vehicle technology in Pessimistic Plug-in Electric Vehicle Technology Scenario with Adaptation.

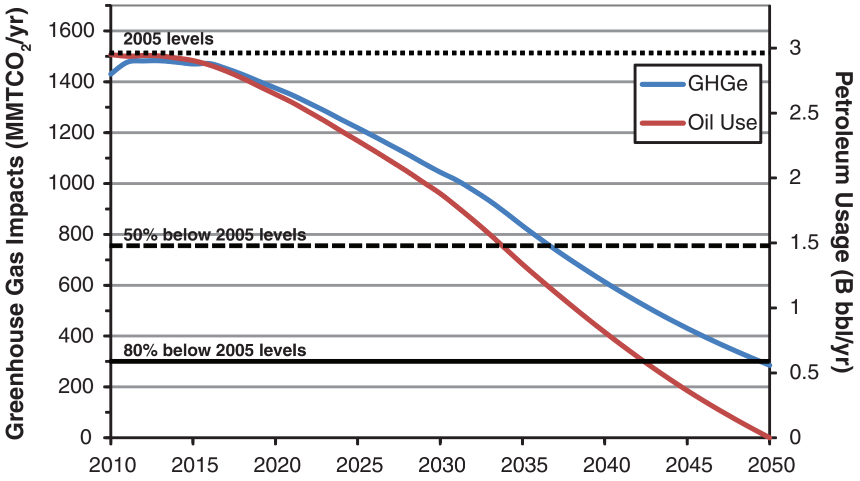

FIGURE 5.37 Changes in petroleum use and greenhouse gas emissions versus 2005 in Pessimistic Plug-in Electric Vehicle Technology Scenario with Adaptation to promote hydrogen fuel cell vehicles after 2024.

If the extreme assumption is made that the two technologies do not progress beyond their status today (BAU assumptions), the same subsidies that induced a sustainable transition in other cases are unsuccessful in achieving any sustainable market penetration. However, far less is spent on subsidies in this pessimistic PEV technology scenario, since the vehicles remain too expensive to attract many buyers. The total expenditures on the unsuccessful attempt to induce a transition amount to somewhat more than $1 billion. Costs exceed benefits, however, and the NPV of the scenario is on the order of –$250 million. Not surprisingly, the goals are not met in 2050, but petroleum use is still 75 percent lower than in 2005 and GHG emissions are 60 percent lower due to the much greater energy efficiency of ICEVs and HEVs and the extensive use of drop-in biofuels.

Suppose that the hypothetical failure of PEV technology to advance is quickly recognized, and that it is observed that FCEV technology is advancing more rapidly than expected. Further, assume that a decision is made to change course 3 to 4 years after the higher PEV subsidies are offered in 2021. Two hundred subsidized hydrogen refueling stations are built in 2024 followed by another 200 in 2025. Subsidies nearly identical to those previously offered for the plug-in vehicles are offered for FCEVs (Figure 5.35). Because it is assumed that the FCEV technology has progressed according to the midrange assumptions, this policy adaptation succeeds, resulting in nearly a 50 percent FCEV market share by 2050 (Figure 5.36). As a consequence, the 2050 goals for both oil and GHG reduction are met (Figure 5.37).

These scenarios are intended to illustrate the importance of uncertainty about future technology evolution and the value of adapting policies to the progress of technology. The choice of technologies for the illustration is entirely arbitrary. Which technology will succeed, if any, is uncertain. There will be costs to attempting to deploy technologies that do not progress to commercial competitiveness. However, if competitive alternatives emerge, and policies can be changed, it may still be possible to meet the long-term goals at a reasonable cost.

5.7 SIMULATING UNCERTAINTY ABOUT THE MARKET'S RESPONSE

In addition to uncertainty about the progress of alternative fuel and vehicle technologies (e.g., Bastani et al., 2012), there is also considerable uncertainty about how the market will respond to novel technologies. Many of the most important determinants of the market success of advanced technologies are poorly understood. These include the inconvenience cost of limited fuel availability for hydrogen and CNG, and limited range and long recharging times for BEVs. The number of innovators willing to pay a premium for novel technologies is largely unknown, as is the amount they would be willing to pay to get one of the first plug-in hybrid electric or hydrogen fuel cell vehicles. And while there are many estimates of consumers' willingness to pay for fuel economy, there is at present no consensus on the subject (Greene, 2010). There are dozens of studies providing estimates of the sensitivity of consumers' vehicle choices to price, yet little is known about the price sensitivity of choices among novel technologies. On the vehicle and fuels supply side, there is a great deal of uncertainty about learning rates, scale economies, and firms' aversion to risk. Furthermore, all these factors can and likely will change over a 40-year period.

It is possible to get a sense of how these uncertainties affect the committee's modeling results by means of simulation analysis. Table 5.6 lists 17 factors that determine market behavior in the LAVE model and provides mean values used in the model runs as well as uncertainty ranges based solely on the committee's judgment. Ten thousand simulations of the LAVE model were run to produce distributions for key model outputs, including the impacts on GHG emissions and

TABLE 5.6 Model Parameters Included in Simulation Analysis and Ranges of Values

Parameters	Distribution	Minimum	Mean	Maximum
Importance of diversity of makes and models to chose from	Triangle	0.50	0.67	0.9975932
Value of time ($/hr)	Triangle	$10.00	$20.00	$39.86
Maximum value of public recharging to typical PHEV buyer	Uniform	$500	$1,000	$1,500
Cost of 1 day on which driving exceeds BEV range	Uniform	$10,002	$20,000	$29,999
Maximum value of public recharging to typical BEV buyer	Uniform	$0	$500	$1,000
Importance of fuel availability relative to standard assumption	Triangle	0.67	1.00	1.67
Payback period for fuel costs (yr)	Triangle	2.0	3.0	5.0
Volume threshold for introduction of new models relative to standard assumptions	Uniform	0.80	1.00	1.20
Optimal production scale relative to standard assumptions	Uniform	0.75	1.00	1.25
Scale elasticity relative to standard assumptions	Uniform	0.50	1.00	1.50
Progress ratio relative to standard assumptions	Uniform	0.96	1.00	1.04
Price elasticities of vehicle choice relative to standard assumptions	Uniform	0.60	1.20	1.80
Percentage of new car buyers who are innovators	Triangle	5.0	15.0	20.0
Willingness of innovators to pay for novel technology ($/mo)	Uniform	$100	$200	$300
Cumulative production at which innovators' willingness to pay is reduced by half	Uniform	1,000,000	2,000,000	3,000,000
Majority's aversion to risk of new technology ($/mo)	Uniform	–$900	–$600	–$300
Cumulative production at which majority's risk is reduced by half	Uniform	$500,000	$1,000,000	$1,500,000

petroleum consumption, and the market shares of advanced vehicle technologies. Not all elements of market uncertainty are included in the simulations. In particular, the LAVE model does not include a representation of industry's likely aversion to risky investments. Nor do the simulation runs include uncertainty about future energy prices.

Two scenarios were simulated: policies to induce a transition to PEVs and policies to induce a transition to FCEVs. Both scenarios include 13.5 billion gallons of drop-in biofuel by 2050 and 10 billion gallons gasoline equivalent of ethanol, as well as the energy efficiency improvements of the midrange scenario.

The resulting uncertainty is strikingly large. The simulated distribution of GHG emissions reductions for the FCEV Policy Case ranges from 43 percent, corresponding to zero market penetration of fuel cell vehicles, to 83 percent at a 60 percent market share of FCEVs (Figure 5.38). It is bi-modal, reflecting the presence of tipping points that cause FCEVs to succeed to a greater or lesser degree, or fail to achieve any significant market share. The existence of tipping points reflects the many positive feedbacks in the transition process. The simulated distribution of greenhouse gas reductions due to plug-in vehicles has a similar bi-modal form and nearly as great a range: –42 to –71 percent (Figure 5.39). The modal separation is less because EVs do not have the strong dependence on fuel availability that hydrogen vehicles do.

The impacts are highly uncertain chiefly because the market response to electric-drive technology is uncertain. The simulated distribution of BEVs' share of the new LDV market in 2050 is shown in Figure 5.40. Although there is a peak in the vicinity of 30 percent, there is a reasonable probability of almost any market share between zero and 50 percent, and a nearly 30 percent probability of almost no market share. The situation for FCEVs is similar but there is a greater separation between market success and failure (Figure 5.41). The simulation analysis can also identify those parameters that have the greatest influence on market success. Both technologies are highly sensitive to assumptions about scale economies in the automotive industry, to the number of innovators and their willingness to pay for novel technology, and to the value to consumers of having a diverse array of vehicles to choose from. BEVs do better if consumers are more sensitive to energy costs and less sensitive to initial price. Consumers' concern about range and recharging-time limitations is also very important for BEVs. Fuel cell vehicles' market success is strongly dependent on the importance of fuel availability, but this factor is of much less importance for BEVs.

There are many reasons that these results should be interpreted cautiously, not the least of which is that a fixed policy strategy is assumed, regardless of the parameter values chosen. As is the case for uncertainty about technological progress, adapting policies to suit the realities of the marketplace would undoubtedly produce better results. All of the frequency distributions shown are conditional on a set of specific policy assumptions that are held constant for all simulations.

The uncertainties illustrated here can be reduced by research and analysis, and by learning from experience. Clearly, there is a great deal of benefit to be gained from a better understanding of both the technologies and the behavior of the market. Uncertainty analysis does not describe the future as it must be or as it will be; it is an attempt to describe

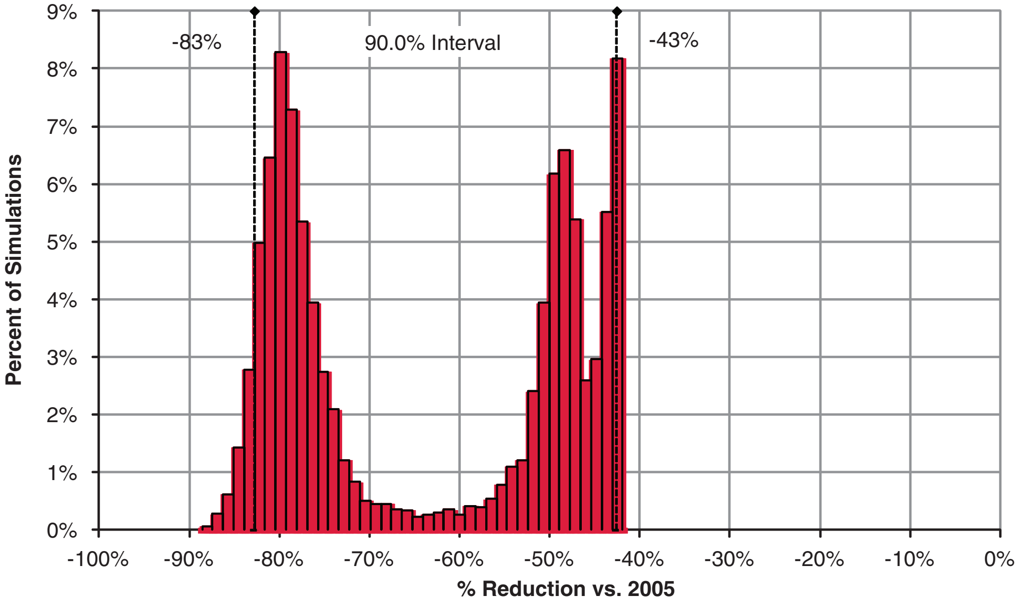

FIGURE 5.38 Distribution of estimated greenhouse gas emissions reductions from 2005 level: Fuel Cell Electric Vehicles Case.

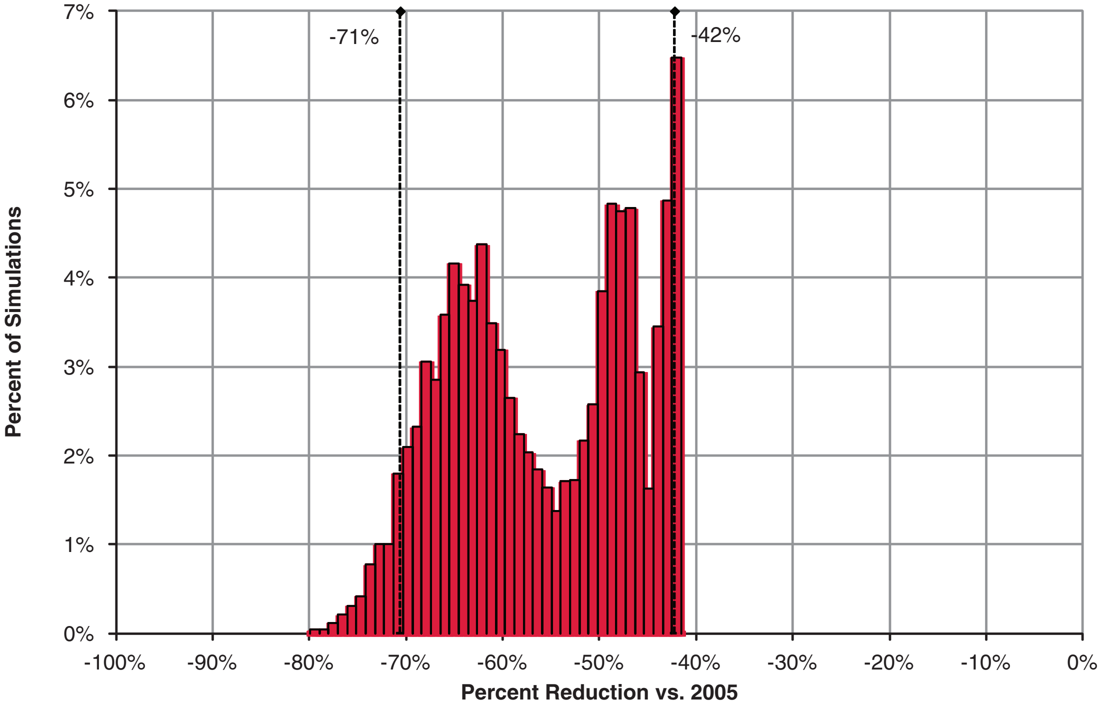

FIGURE 5.39 Distribution of estimated greenhouse gas reduction in 2050 from 2005 level: Plug-in Electric Vehicles.

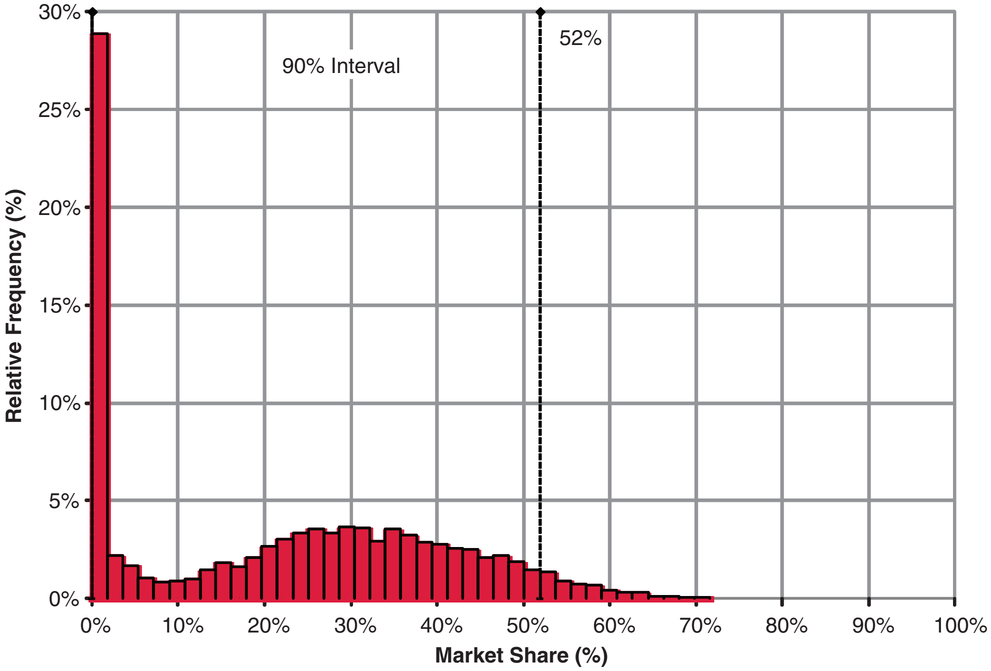

FIGURE 5.40 Distribution of battery electric vehicle market share in 2050: Plug-in EV Policy Case.

what we think we do and do not know about the distant future, as viewed from the present. Learning—increasing knowledge of the processes and behaviors that will affect a transition, as well as the costs and performance of the technologies that could enable one—is likely to be essential if the 2030 and 2050 goals are to be achieved efficiently. Inducing a transition to non-petroleum energy sources with extremely low GHG emissions is an unprecedented challenge for public policy. To support effective policy making, a much better understanding of how markets and technology will interact is likely to be highly beneficial.

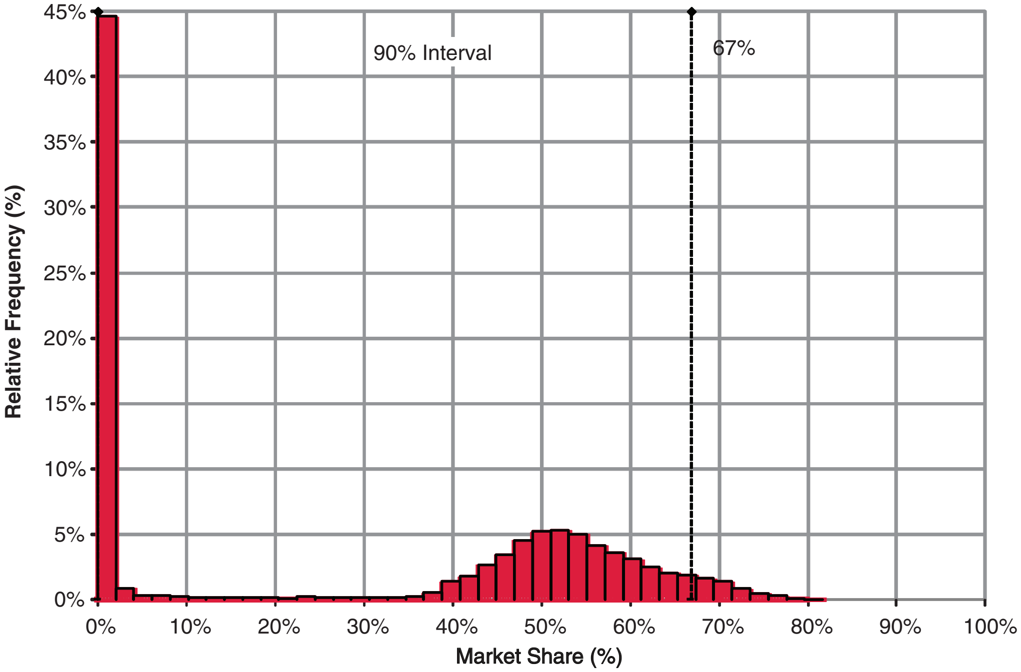

FIGURE 5.41 Distribution of hydrogen fuel cell vehicle market share in 2050: Fuel Cell Electric Vehicle Policy Case.

5.8 FINDINGS

Large and important reductions in petroleum use and greenhouse gas emissions can be achieved by increasing the fuel economy of light-duty vehicles in line with the CAFE standards for 2025 and embodied in the RFS2 (25-30 percent by 2030 and 30-40 percent by 2050). Even greater reductions will be possible if advances in vehicle and fuel technologies beyond those required to meet the 2025 CAFE standards and the RFS2 standards can be realized.

Achieving the 2030 and 2050 goals for reduction of oil use and greenhouse gas emissions will require a mix of strong public policies, market forces that encourage greater energy efficiency, and continued improvements in vehicle and fuels technologies. As the comparison of VISION and LAVE-Trans model estimates illustrates, reaching the goals is likely to be more difficult than previous "what if" analyses have concluded due to economic feedback effects and competition among technologies and fuels. These feedback effects include increased vehicle use with reduced energy costs, increased new-vehicle demand with improved technology, and competition for market share among advanced technologies. They are also almost certain to include lower petroleum prices as a consequence of reduced petroleum demand, although no attempt has been made to model that in these analyses. These feedback effects are much smaller in magnitude than the direct effects of energy efficiency improvement and displacement of petroleum with alternative energy sources; still, they increase the difficulty of achieving the 2050 goals.

Achieving a 40 percent reduction in petroleum use over 2005 levels by 2030 is a more realistic and achievable goal than a 50 percent reduction. Whether or not this level of reduction would be sufficient to achieve the objective of solving the nation's oil dependence problem given expected increases in domestic petroleum supply should be carefully evaluated.

Even if the nation should fall short of the 2050 goals, there are likely to be environmental, economic, and national security benefits resulting from the reductions that are achieved. The committee's modeling suggests that reductions in petroleum use on the order of 70 to 90 percent are possible given very strong policies and continued advances in the key technologies: electric-drive vehicles (hybrid, plug-in hybrid, battery, and fuel cell) and drop-in biofuels. In the committee's judgment, reductions in greenhouse gas emissions on the order of 60 to 80 percent are possible but will require effective and adaptive policies over time as well as continued advances in the technologies described in Chapters 2 and 3.

Including the social costs of GHG emissions and petroleum dependence in the cost of fuels (e.g., via a carbon tax) provides important signals to the market that will promote technological development and behavioral changes. Yet these pricing strategies alone are likely to be insufficient to induce a major transition to alternative, net-low-carbon vehicle technologies and/or energy sources. Additional strong, temporary policies may be required to break the lock-in of conventional technology and overcome the market barriers to alternative vehicles and fuels.

If two or more of the fuel and/or vehicle technologies evolve through policy and technology development as shown in a number of the committee's scenarios, the committee's model calculations indicate benefits of making a transition to a low-petroleum, low-GHG energy system for LDVs that exceed the costs by a wide margin. Benefits include energy cost savings, improved vehicle technologies, and reductions in petroleum use and GHG emissions. Costs refer to the additional costs of the transition over and above what the market is willing to do voluntarily. However, as noted above, modeling results should be viewed as approximations at best because there is by necessity in such predictions a great deal of uncertainty in estimates of both benefits and costs. Furthermore, the costs are likely to be very large early on with benefits occurring much later in time.

Depending on the readiness of technology and the timing of policy initiatives, subsidies or regulations for new vehicle energy efficiency and the provision of energy infrastructure may be required, especially in the case of a transition to a new vehicle and fuel system. In such cases, substantial subsidies might be required for at least 5 to 10 years, and possibly as long as 20 years if technological progress is slow (e.g., starting grid-connected vehicles now is likely to require 20 years of subsidy to stabilize them at a significant market share). And, as shown above, there is likely to be a high degree of risk in policies targeted to a particular technology. For these reasons, it is important to consider carefully when and if such policies are necessary and to make policy adaptable to changing evidence about technology and market conditions. It is also very important that policy makers obtain objective, expert advice on the readiness of both fuel and vehicle technologies and markets. Scenario analysis has identified strong tipping points for the transition to new vehicle technologies. If sufficiently large subsidies are not applied to overcome the early cost differentials, then the transition will not occur and the subsidies will have been wasted. In pursuing these goals, the rate of cost decline and the subsidies applied at each stage must be carefully weighed to establish that the program is effective.

Advance placement of refueling infrastructure is critical to the market acceptance of hydrogen fuel cell and CNG vehicles. It is likely to be less critical to the market acceptance of grid-connected vehicles, since many consumers will have the option of home recharging. However, the absence of an outside-the-home refueling infrastructure for grid-connected vehicles is likely to depress demand for these vehicles. Infrastructure changes will not be needed if the most cost-effective solution evolves in the direction of more efficient ICEVs and HEVs combined with drop-in low-carbon biofuels.

Empirical knowledge of the barriers to major energy transitions is currently inadequate to make robust assessments of public policies. The modeling analysis presented in this chapter is intended to be an initial step in the right direction rather than a definitive assessment of alternatives. Research is needed to better understand key factors for transitions to new vehicle fuel systems such as the costs of limited fuel availability, the disutility of vehicles with short ranges and long recharge times, the numbers of innovators and early adopters among the car-buying public, as well as their willingness to pay for novel technologies and the risk aversion of the majority, and much more. More information is also need on the transition costs and barriers to production of alternative drop-in fuels, especially on the type of incentives necessary for biofuels. The models that the committee and others have used to analyze the transition to alternative vehicles and/or fuels are first-generation efforts, more useful for understanding processes and their interactions than producing definitive results.

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6

Policies for Reducing GHG Emissions from and Petroleum Use by Light-Duty Vehicles

To reach the twin goals addressed in this study, significant changes in policy will be needed to induce a move toward vehicle-fuel systems whose petroleum demand and greenhouse gas (GHG) emissions are very different from those of today. The modeling and results from Chapter 5 suggest a range of possible policy and technology pathways by which these goals might be met. This chapter reviews policy options, including those analyzed in Chapter 5 (for example, vehicle fuel economy and GHG standards and renewable fuel standards), that may offer promise. Each policy is described and assessed based on evidence about its use, effectiveness, and any shortcomings. Policy suggestions based on these assessments are provided in Chapter 7.

The policies needed to reach the goals for reductions in petroleum use and GHG emissions will have to differ dramatically from those of the past and could incur a high up-front cost. However, as the modeling results in Chapter 5 illustrate, these costs may be more than recouped in later years.

Policies are needed that can promote major changes in direction in the extensive private investments associated with vehicle manufacturing, fuel production and related infrastructure—changes that in turn will affect the market decisions made by consumers and businesses which ultimately shape such investments. The extent to which the resulting transition to a low-petroleum light-duty vehicle (LDV) system with low net GHG emissions will require displacing the incumbent internal combustion, liquid fueled vehicle technology is not known. However, major changes clearly will be needed in the use of natural resources and in the impacts of GHG emissions associated with supplying LDV fuels. Given the inherent uncertainties, an adaptive policy framework is needed that will be responsive to markets, technologies, and progress toward achieving the goals.

6.1 POLICIES INFLUENCING AUTOMOTIVE ENERGY USE AND GREENHOUSE GAS EMISSIONS

Several arenas of policy are relevant as means of influencing automotive energy use and GHG emissions: land-use, transportation, energy, environmental protection, and technology. These arenas are interrelated and the relationships are sometimes implicit. Failure to recognize the interrelationships between policy arenas could result in poor coordination or even contradictions among policy signals. Some of the relationships have been made explicit as policy makers have realized, for example, the interactions between land-use planning and transportation planning. The challenge of achieving deep reductions in petroleum use and GHG emissions requires an even greater degree of coordination among the policy arenas influencing the LDV sector.

Figure 6.1 shows on a normalized scale the total nationwide levels of several key LDV-related impacts that have been a subject of public policy. From 1970 through 2005, light-duty vehicle miles traveled (VMT) increased by 160 percent. Over the same period, gains in fuel efficiency held LDV petroleum demand and CO_2 emissions to a 74 percent increase. Modest absolute declines were achieved for traffic fatalities. The greatest improvement was seen in vehicle conventional air pollution, which achieved an absolute reduction of 65 percent by 2005 relative to its 1970 level.

6.1.1 Land-Use Policy

Land-use policies are perhaps the deepest foundation of the automotive system, helping, along with geography, to shape transportation patterns through the ages. U.S. land-use governance remains highly localized, and many levels of administration are involved in the planning, permitting, and

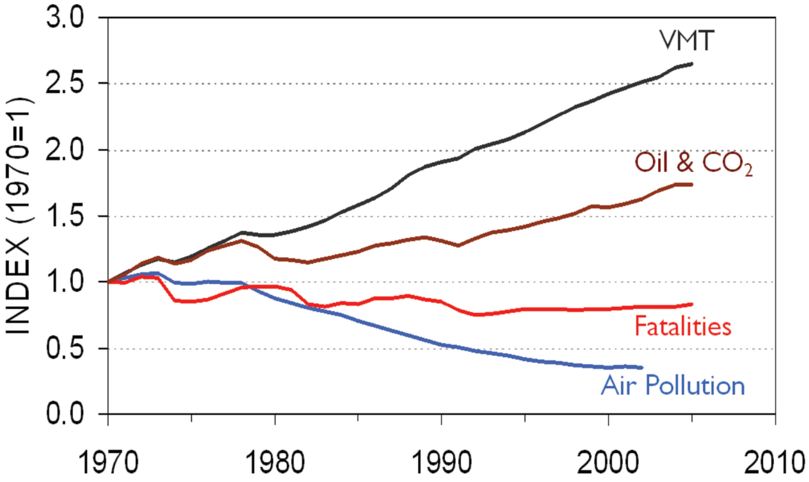

FIGURE 6.1 Trends in impacts of U.S. light-duty vehicles.
SOURCE: DOT, DOE, and EPA statistics.

zoning of land use. Higher levels of government traditionally show substantial deference to local prerogatives.

Academic understanding of the links between land use and transportation has translated only slowly into policies that might restrain travel demand growth tied to land use. Researchers have identified five land-use features, the "five Ds," influencing demand for automobile travel: population **d**ensity, land-use **d**iversity, neighborhood **d**esign, major **d**estination accessibility, and transit stop **d**istance from departure and arrival points of transit stops (TRB 2009, p. 52).

Although only recently considered in the context of transportation-related petroleum demand and GHG emissions, programs that support or constrain the expansion of croplands and managed forests used for sourcing biofuel feedstocks or for carbon sequestration through afforestation and grassland restoration are another important aspect of land-use policy. Determining the optimal use of land with respect to climate protection raises issues that may require rethinking of such policies (Righelato and Spracklen, 2007; Wise et al., 2009; Zhang et al., 2008).

6.1.2 Transportation Policy

Transportation policies center on the provision and operation of the infrastructure needed for mobility. For the automobile, they have focused on building, maintaining, and supporting roadways. In urban areas, transportation policy also supports mass transit, as well as sidewalks and bike paths, and so affects the availability and affordability of alternatives to auto travel. There is a clear emphasis in the U.S. Department of Transportation's (DOT's) official mission statement on ensuring speed of conveyance as well as safety and efficiency. With the automobile being by far the dominant mode of transportation for most Americans, facilitating auto travel has been a major part of DOT's mission. Much of the necessary investment for highways and major roads is accomplished through a federal-state partnership approach, while most local roads are handled by municipalities with varying degrees of state involvement.

A key financial reason for the success of automobiles is that the vehicles themselves are purchased by individual consumers, who also pay for operating costs, notably fuel. That leaves to government the provision and maintenance of infrastructure. This contrasts with public transit modes, which require a public or public-private partnership to acquire and operate the vehicles and their supporting infrastructure. Consumers ultimately pay for all aspects of any transport system, with taxes or other user fees supporting the publicly provided elements.

6.1.3 Energy Policy

U.S. energy policies have roots in natural resource policy. Most pertinent to the auto sector are policies that have facilitated the development of petroleum resources over the years and those related to ensuring access to overseas supplies and securing them vis-à-vis geopolitical considerations. On the domestic front, policies supporting the economic development of oil and gas resources confronted environmental considerations and the need to balance competing players' demands for use of lands and offshore locations. Thus, the U.S. Department of the Interior long has been involved in petroleum-related activity. The Energy Research and Development Administration was created in 1974, and its successor, the U.S. Department of Energy (DOE) was formed in 1977, following the 1970s petroleum crisis.

In recognition of the importance of petroleum for military operations and as a critical resource for the entire economy, efforts to secure and expand the supply of petroleum have long been and continue to be a key part of U.S. energy policy.

The 1973-1974 energy crisis prompted the development of policies to encourage energy conservation and promote alternatives to petroleum. The LDV fleet became a key target, and vehicle efficiency standards known as the Corporate Average Fuel Economy, or CAFE, standards, were enacted as part of the Energy Policy and Conservation Act of 1975 (P.L. 94-163). A "gas-guzzler" tax followed in 1978 with passage of the Energy Tax Act (ETA; P.L. 95-618).

The 1970s also saw the development of policies to support alternatives to petroleum ranging from synthetic fossil fuels to biofuels. The ETA also introduced an excise tax exemption for gasohol,[1] which subsequently was extended and transformed into a tax credit for ethanol, the volumetric ethanol excise tax credit (VEETC), which until recently stood at \$0.45 per gallon of ethanol. A tariff was imposed on imported ethanol to foster domestic biofuel production. Both the tax credit and the tariff expired at the end of 2011.

The CAFE credits program for alternative fuel vehicles (AFVs) was created by the Alternative Motor Fuels Act of 1988 (P.L. 100-94). It provided credit incentives for the manufacture of vehicles that used alcohol or natural gas fuels, either exclusively or as an alternative to gasoline or diesel fuel. This program induced automakers to sell a large number of dual-fuel vehicles capable of running on E85. However, for a variety of reasons including limited availability of E85 retail outlets, the program has not fostered significant use of alternative fuels (DOT-DOE-EPA, 2002). The Energy Policy Act of 1992 (EPAct; P.L. 102-486) established an expanded set of incentives and programs to promote alternative fuels and AFVs. They include mandates for AFV use in the federal fleet and certain state and utility fleets, and authorization for federal support of voluntary AFV deployment programs, which were subsequently implemented by DOE through the Clean Cities program.

Among the most recent developments in U.S. energy policy with respect to the LDV sector is the Renewable Fuel Standard (RFS) instituted as part of the 2005 EPAct (P.L. 109-58). The RFS put in place for the first time a nationwide mandate for use of a fuel other than petroleum. The 2005 EPAct also included expanded incentives for the production and commercialization of a range of AFV technologies. It included tax incentives for AFVs and infrastructure for alternative fuels that are not drop-in fuels. Incentives were provided on a graduated scale to encourage the production of different AFVs (DOE-EERE, 2011a; TIAP, 2012). Metrics related to technical fuel efficiency were used to determine the level of incentives. The incentives were limited to the first 60,000 qualifying vehicles produced by any one automaker.

Tax credits initially were for hybrid-electric, battery-electric, and fuel-cell electric vehicles and for qualified diesel and natural gas LDVs. Numerous modifications have occurred over the years and Congress allowed the tax credits for hybrid electric vehicles, and diesel and natural gas vehicles to expire at the end of 2010. Tax credits for battery-electric motorcycles, three-wheeled electric vehicles, and low-speed neighborhood-electric vehicles expired at the end of 2011, as did a credit for converting conventional gasoline and diesel vehicles to plug-in hybrid or all-electric propulsion systems.

Currently, under the American Recovery and Reinvestment Tax Act and the Emergency Economic Stabilization Act of 2008, the United States uses a program that extends a federal tax credit of up to \$7,500 to buyers of qualified plug-in hybrid and battery-electric LDVs. The credit is applicable in the year of the vehicle's purchase. Subsequent legislation limits the credit to the first 200,000 eligible vehicles from each qualified automaker. When that threshold is reached, the tax credit for subsequent vehicles sold is reduced in stages, disappearing completely after six calendar quarters.[2] Fuel-cell electric vehicles remain eligible for a federal tax credit of \$4,000-\$8,000, depending on their fuel economy ratings, but it is scheduled to expire in 2014.

In December 2007, the Energy Independence and Security Act (EISA; P.L. 110-140) expanded the RFS to target 35 billion gallons of ethanol-equivalent biofuels plus 1 billion gallons of biomass-based diesel by 2022, with life-cycle GHG emissions stipulations designed to foster cellulosic and other advanced biofuels. The same legislation raised the combined light-duty fleet CAFE standard to a 35 mpg level by 2020 while authorizing other structural reforms in the standards. The EISA also established a loan guarantee program for construction of manufacturing facilities for advanced-vehicle batteries and battery systems and requires a phase-out of the dual-fuel vehicle CAFE credit program by 2020.

6.1.4 Environmental Policy

Because automobiles and their supporting infrastructure impact the environment in numerous ways, many aspects of environmental policy come into play. However, it is control of the direct emissions from motor vehicles that is most relevant.

The history of Los Angeles smog, the pioneering work of Arie Haagen-Smit in linking smog to tailpipe pollution, and the subsequent development of emissions regulations first in California and then federally with the broad authority established by the Clean Air Act (CAA 1970) all are elements of one of the iconic stories of U.S. environmental policy (Mondt, 2000; CARB, 2011). At the beginning of this process in the 1960s, air pollution science was in its infancy and controls were rudimentary. As development continued, progressively tighter standards were set for restricting tailpipe emissions, prescribing fuel formulations, and limiting fuel evaporation from vehicles and fuel pumps.

The most stringent regulations for combustion-based vehicles, such as California's partial zero emission vehicle

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[1] A fuel consisting of a blend of gasoline and ethanol.

[2] This tax credit is described in greater detail at http://www.fueleconomy.gov/feg/taxevb.shtml, accessed February 6, 2012.

standard, cut emissions per vehicle-mile by over two orders of magnitude, reducing an LDV's direct conventional air pollution impacts to nearly negligible levels. Quantitatively, the CAA policies addressing emissions have been by far the most effective areas of policy, resulting in a substantial absolute reduction of conventional pollution from LDVs even in the face of rising VMT (see Figure 6.1).

The CAA's overarching requirement for healthy air, embodied in the National Ambient Air Quality Standards (NAAQS), is what ultimately anchors the policy. The law obligates the U.S. Environmental Protection Agency (EPA) to pursue fact-based assessments of air pollutants' impacts on public health and welfare and to promulgate NAAQS solely on that basis. Economic considerations can enter in only when EPA develops the regulations that determine how the NAAQS will be met.

The Supreme Court (2007) interpreted the CAA's definition of air pollutants to include greenhouse gases and said that they could be subject to regulation if found to endanger public health or welfare. The EPA subsequently made such an "endangerment" finding (2009), setting in motion a regulatory process that started with GHG emissions standards for motor vehicles and is being extended to other sources.

6.1.5 Technology Policy

A large number of policy measures have the potential to influence technical innovation in LDVs and fuels. The federal department involved most actively in directly promoting new automotive technology has been the DOE. Its role primarily has been one of funding basic science and engineering research related to vehicles and fuels and pursuing demonstration and deployment programs that might foster market adoption of the technologies developed. Many National Research Council (NRC) studies reviewed this research, development, demonstration, and deployment approach while suggesting refinements and highlighting the challenges and obstacles involved. Examples of such energy technology policy programs include the Advanced Battery Consortium, the Partnership for a New Generation of Vehicles, the hydrogen-oriented FreedomCAR program, and the present US DRIVE program that emphasizes electric vehicles and plug-in hybrids. From the 1970s forward, parallel efforts have been aimed at developing renewable fuels.

6.1.6 Decision Making Through the Matrix of Policy Arenas

Based on methods of technology assessment and economic analysis as discussed below in this chapter, policy measures are established through a matrix of policy arenas such as those outlined above. The preceding overview of the different arenas of public policy that influence the LDV sector—transportation, land use, environmental protection, energy, and technology—underscores the complexity of the challenge from a practical policy-making perspective. A national decision to reach goals such as those given in this committee's statement of task will likely need to involve all of these different policy arenas and the associated diversity of congressional committees, federal agencies, and stakeholder interests, along with an analogous range of interests at state and local levels of government. Reaching a national decision to achieve the goals will be a complicated undertaking that requires an adaptive policy framework as discussed below in this chapter.

6.2 WAYS TO INFLUENCE PETROLEUM USE AND GHG EMISSIONS EFFECTS IN THE LDV SECTOR

Policies that affect petroleum use, GHG emissions, or both ultimately exert their influence through a few key parameters:

- Vehicle energy intensity—typically, the energy required to move the average vehicle of the on-road LDV fleet 1 mile;
- Petroleum share of the energy used to power LDV fleets (when energy security and dependence on petroleum is the issue) or net GHG emissions balance of the fuel system (when climate disruption is the issue); the latter is often described as the average well-to-wheels GHG emissions of the energy used to power the vehicle fleet;[3] and
- Volume of travel—typically, the VMT by the on-road LDV fleet.

It sometimes is argued that system efficiency constitutes an independent fourth parameter, but that is not the case. Policies that affect system efficiency influence GHG emissions or petroleum use only through one or more of the three parameters listed above.[4]

A common analytic framework for transportation energy and climate-change analysis involves factoring emissions based on the three key parameters, which interact multiplicatively. Addressing all three (vehicle energy intensity, petroleum share of energy use in LDVs, and travel activity) is important because a policy that focuses only on a single parameter is likely to require it to be pushed to extraordinary lengths.[5]

Whether the policies target one or more of the parameters, they operate by influencing market actors whose decisions determine the values of the parameters, which in turn determine LDV petroleum use and GHG emissions. Policies that

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[3] For advantages and disadvantages of the use of well-to-wheels approaches to regulating GHG emissions related to fuels, see below.

[4] However, in view of the interest in policies promoting system efficiency, they are discussed below in this chapter.

[5] For example, the average on-road fleet fuel economy would have to exceed 180 mpg if vehicle energy intensity were the only parameter targeted for reducing LDV petroleum use; see footnote 2 in Chapter 2.

target one parameter may influence others. A well-known example is the difference in impact on vehicle GHG emissions and energy use produced by motor fuel taxes versus efficiency standards. Motor fuel taxes stimulate demand for more fuel-efficient vehicles. They also raise the variable cost of driving, which in turn reduces VMT. In contrast, fuel economy standards require the sale of more fuel-efficient vehicles, *reducing* the cost of driving, thereby *increasing* VMT. CAFE is effective at pushing new technology into the fleet but is unlikely to affect the size of vehicles that consumers purchase (at least with the current footprint-based system). Taxes discourage people from driving more and encourage consumers to purchase smaller vehicles. The benefits of CAFE and taxes are largely independent of one another. Both policies have been found to reduce LDV fuel use overall, but the *amount* by which each policy reduces total LDV petroleum use or GHG emissions differs.

Finally, the cost of reducing emissions by changing any single parameter is likely to rise as the magnitude of required change increases or the time over which the required change is to be accomplished decreases.

Policies such as carbon pricing that affect more than a single parameter are generally considered by economists to be most cost-effective.

Vehicle energy intensity, petroleum share of the fuel market, and travel demand each is an outcome of market decisions. Thus, the market actors whose decisions affect each of the parameters (and whose decisions on one parameter can affect their decisions on another) have to be examined in assessing policy options.

In general, the ultimate actor is the consumer—the owner or other end user of LDVs who purchases vehicles and fuel and, through tax dollars, user fees, and bundled transactions, also pays for roads and other parts of the transportation infrastructure. Through factors including their choices of where to live, work, and shop, consumers determine the urban-regional forms and broader built environment that automotive transportation shapes and serves.

The markets that influence LDV petroleum use and GHG emissions involve cash flow from consumers or other end users to the suppliers of transportation-related products and services, most notably, the automobile industry and the motor fuels industry.[6] In most cases, policies designed to influence decisions about motor vehicle purchase and use are directed at these entities rather than at the consumer.[7] For example, motor vehicle fuel economy standards are imposed on vehicle manufacturers, not vehicle purchasers. The penalties for not meeting such standards are directly imposed on these firms and, along with the costs of meeting the standards, may be wholly or in part passed onto consumers. It is therefore left to vehicle manufacturers and fuel producers not only to develop and produce the products required to meet the regulations to which they are subject but also to generate the economic signals that induce the purchase of their products in the required quantities by consumers.

6.3 POLICIES AIMED AT REDUCING VEHICLE ENERGY INTENSITY

The ultimate aim of policies to reduce vehicle energy intensity is to lower the average actual on-road fuel consumption of the total LDV fleet. There are two broad approaches available for achieving this. The first is to reduce the average fuel consumption of the typical new vehicle, in all size classes, largely through incorporating technologies that reduce fuel consumption. The second is reduce or eliminate the heaviest and thus least efficient vehicles in the LDV fleet by encouraging the purchase and use of lighter vehicles, which can lead to reduced performance or utility (e.g., reduced load-carrying ability or acceleration). Individual policies can emphasize one of these two approaches, can encourage one while discouraging the other, or can be neutral.

6.3.1 Vehicle Energy Efficiency and GHG Emissions Standards

Several countries have enacted standards that mandate the level of energy efficiency or the level of CO_2 emissions that the average newly produced vehicle must achieve by a certain date. Anderson et al. (2011), Eads (2011), and An et al. (2007) describe the vehicle efficiency and GHG emissions standards programs that are in place or under development around the world. The CAFE standards have been in effect the longest, have been studied extensively, and are most pertinent to the committee's task.

6.3.2 U.S. CAFE Standards

The initial CAFE standards were enacted as part of the 1975 Energy Policy and Conservation Act (see Figure 2.1 for historical and projected LDV vehicle fuel economy). Although the U.S. standards are considered to be regulatory rather than economic, they are enforced through economic penalties. Manufacturers whose annual factory sales of vehicles do not meet the CAFE standards for each of their fleets (domestic and imported cars and domestic and imported trucks) must pay a civil penalty.[8] For the 2011 model year,

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[6] Although the complex interactions and transactions that determine the provision of transportation infrastructure, associated land-use patterns, and related services are difficult to characterize as a distinct "market," they also involve a set of actors whose decisions can be viewed through an economic lens.

[7] There are exceptions. As is discussed below, "feebates"—subsidies for more fuel-efficient vehicles and taxes on less fuel-efficient ones—cause resources to flow directly between the government and consumers. The same thing is true of direct tax credits.

[8] "Factory sales" are sales by the manufacturer to the dealer. Therefore, the number of vehicles of a certain model year actually reaching the con-

the penalty was $5.50 for each tenth of a mile per gallon that the manufacturer's average fuel economy fell short of the standard, multiplied by the total volume of vehicles in the affected fleet (EPA, 2009). As of July 2011, NHTSA had collected a total of $795 million in civil penalties over the life of the CAFE program (NHTSA, 2011).

6.3.2.1 The Lag Between the Fuel Economy of New Vehicles and That of the On-Road Fleet

There is a significant difference between the fuel economy of the average new vehicle and that of the average on-road vehicle. The average LDV's lifetime has been increasing and, according to R.L. Polk, is now about 10.8 years (R.L. Polk and Company, 2011). Vehicles are driven less as they age, and so it takes about 15 years for the age- and travel-weighted average fuel economy of the on-road fleet to reach 90 percent of the average level of new vehicles in a given year, based on the most recently published vehicle survivability statistics (NHTSA, 2006). The CAFE standards apply only to the new-car fleet, and rarely has an effort been made to impact the pace of fleet turnover.[9]

6.3.2.2 Recent Changes in the U.S. CAFE Standards

In 2007, new legislation set a fuel economy target of 35 mpg (2.9 gal/100 mi) for the combined LDV fleet of cars and trucks, to be achieved by model year 2020.[10] The legislation authorized NHTSA to set standards on the basis of vehicle attributes. The agency settled on vehicle "footprint," defined as the track width times the wheelbase, as a basis for all LDV standards, building on the similar approach adopted in the 2006 CAFE reform rule for light trucks. Therefore, CAFE standards now vary with the size mix of an automaker's fleet (Box 6.1). Pursuant to the Obama Administration's agreement with automakers and other parties to develop a single national program for CAFE standards in coordination with federal and California LDV GHG emissions standards, a more ambitious target date was set, requiring that a 35.5 mpg CAFE-equivalent (counting non-fuel-economy-related GHG emissions) new fleet average be met by model year 2016 (EPA and NHTSA, 2010). This target implies an annual rate of improvement in average new LDV fleet fuel economy of 5 percent.

In November 2011, NHTSA and EPA jointly published a Notice of Proposed Rulemaking to further strengthen CAFE standards and GHG emissions standards for LDVs for the model year (MY) 2017-MY2025 period. The agencies proposed an increase in the standards to a MY2025 target of 54.5 mpg, with GHG emissions reductions (CO_2 equivalent) corresponding to a fleet average of 163 g/mi (EPA and NHTSA, 2011). In fuel economy terms, the agencies project LDV fleet average compliance levels of 40.9 mpg (2.4 gal/100 mi) in 2021 and 49.6 mpg (2.0 gal/100 mi) in 2025. The agreement would provide CAFE credits for the production of vehicles employing certain advanced technologies. The initial 5-year phase, for MY2017-MY2021, provides for a slower rate of increase for light trucks, averaging 2.9 percent per year, compared to a 4.1 percent increase in passenger car standards for the same period. The program also provides for a comprehensive mid-term evaluation prior to finalization of the MY2022-MY2025 standards. Although subject to revision under the mid-term review, the rates of increase proposed for the second phase of the program, covering MY2022-MY2025, are 4.7 percent per year for light trucks and 4.2 percent per year for passenger cars. The projected average annual rate of fuel economy increase for the recently finalized and currently proposed CAFE regulations is 3.6 percent per year over the 2010-2025 period, rising from an achieved MY2010 compliance level of 29.3 mpg (NHTSA, 2012)

These two rulemakings reflect a significant change in the way CAFE standards are developed and issued. Previously, the task had been solely the responsibility of NHTSA, in consultation with other agencies such as the EPA. The standards applied only to the fuel economy of new vehicles. However, NHTSA and the EPA issued the final MY2010-MY2016 standards jointly, and the MY2017-MY2025 standards are being developed and proposed by both agencies in order to address the fuel economy of vehicles and the GHGs they emit.

NHTSA's authority for issuing fuel economy standards remains the 1975 Energy Policy and Conservation Act,

BOX 6.1
The "Footprint" Approach

According to the "footprint" formula now used in computing CAFE, in model year 2016 a compact car such as the Honda Fit, with a model footprint of 40 square feet, would have a fuel economy target of 41.4 mpg (2.42 gal/100 mi), while a full size car, such as the Chrysler 300, with a model footprint of 53 square feet, would have a fuel economy target of 32.8 mpg (3.05 gal/100 mi). A large pickup truck such as the Chevrolet Silverado, with a model footprint of 67 square feet, would have a fuel economy target of 24.7 mpg (4.05 gal/100 mi).

SOURCE: Davis et al. (2011), Table 4-19.

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sumer differs somewhat from that model year's factory sales. Manufacturers can carry forward or backward excess CAFE credits for 3 model years in order to offset any shortfalls to a given fleet. Manufacturers cannot transfer credits between fleets or between manufacturers. Penalties are assessed for a given model year and fleet if any shortfall in CAFE during that model year is not offset by these credits (NHTSA, 2012).

[9] The most notable exception was the "Cash for Clunkers" program adopted by the Obama Administration in 2009. This is discussed in more detail below.

[10] This legislation was the Energy Independence and Security Act.

as amended by the 2007 EISA. EPA's authority for GHG emissions standards is the CAA. The factors NHTSA may consider in developing fuel economy standards are not precisely the same as the factors that EPA may use in developing GHG emissions standards, and so the promulgation of a rule covering both fuel economy and GHG emissions requires a considerable amount of interagency coordination to ensure a consistent set of requirements. An additional level of coordination is involved because the state of California, subject to EPA waiver of the CAA preemption provision, has authority to set its own motor vehicle emissions standards. California has agreed to harmonize its standards with the EPA and NHTSA under the single national program terms.

6.3.3 Subsidies for More Fuel-Efficient Vehicles and Fees on Less Fuel-Efficient Vehicles

Another policy for encouraging the production and sale of vehicles that are more fuel-efficient and/or emit less CO_2 is to use subsidies, taxes, or both, based on fuel use, CO_2 emissions, or a combination. In the United States, a gas guzzler tax was established by the Energy Tax Act of 1978. Phased in over 1981-1985, this program now involves a graduated level of taxation on passenger cars having a fuel economy below 22.5 mpg (regulatory level, as used for CAFE standards).[11] The gas guzzler tax is proportional to the increase in fuel consumption rate above that of a 22.5 mpg car and the current maximum is $7,700 on cars rated at less than 12.5 mpg. The gas guzzler tax does not apply to light trucks and for at least the past two decades has applied to only a small fraction of vehicles, typically high-performance sports and luxury cars. In its early years, the gas guzzler tax was effective in helping to motivate fuel economy improvements in the least efficient cars in the fleet (Khazzoom, 1994; DeCicco and Gordon, 1995). Japan, many countries in Western Europe, and a few others have had graduated vehicle taxation schedules based on fuel consumption, engine displacement, or some other metric defined for tax purposes. Some of these programs have been recast in recent years to be based on vehicle CO_2 emissions rate.

When subsidies for efficient vehicles are added to a vehicle taxation program, it becomes what is referred to as a "feebate" program. Such a program was under discussion as part of the response to the 1973 energy crisis (Difiglio, 1976), but only the gas guzzler tax portion was implemented. Over the years, feebate programs were proposed in a number of states but were never enacted. In 1991, the Canadian Province of Ontario enacted a tax for fuel conservation that levied modest graduated taxes on inefficient vehicles and provided subsidies for a subset of efficient vehicles.

In recent years, France has pursued a feebate-type program, known as the "bonus-malus" system, applied at the time of purchase of a vehicle (Bastard, 2010). The amount charged ("malus") or rebated ("bonus") depends on the vehicle's CO_2 type approval test emissions figure.[12] Originally, the amounts ranged from a bonus payment of €1,000 for cars rated under 100 g/km to a fee of €2,600 for cars rated above 250 g/km. A bonus payment of €5,000 applied for vehicles with a CO_2 emissions value below 60 g/km. The incentive provided by these bonus-malus values has been estimated to be broadly equivalent to €150/metric ton of CO_2 (Bastard, 2010).

According to Bastard (2010), "the system demonstrated high effectiveness: in 2008, CO_2 emissions from new vehicles in France fell by 9 g/km compared to 2007, falling from 149 g/km to 140 g/km, most of the decrease resulting from the bonus-malus system." The decrease resulted from three separate impacts: (1) a downsizing in the segment mix, (2) a downsizing in power, and (3) a move to diesel in certain segments. The measure was intended to be revenue neutral, but has turned out to have a net cost for the French state, as the shift in the market to smaller vehicles was higher than anticipated. Bastard estimates that the net budgetary cost was approximately €200 million in 2008 and €500 million in 2009.[13]

6.3.4 Motor Fuel Taxes as an Incentive to Purchase More Fuel-Efficient Vehicles

A third type of policy to incentivize the purchase of more fuel-efficient vehicles is motor fuel taxes. Nearly every country levies taxes on motor fuel, but the level of tax varies widely. Table 6.1 shows the variance in motor fuel taxes for several major developed countries, in 1990 and in 2010.

Fuel prices impact both vehicle purchase decisions with respect to fuel economy and how much vehicles are driven. The sum of these impacts is measured by the elasticity of demand for fuel—defined as the percentage change in fuel purchased divided by the percentage change in fuel price. This elasticity has been estimated by many studies, which generally differentiate between short-term (2 years or less) and long-term (more than 2 years) elasticity. Short-term elasticity generally is interpreted as reflecting changes in VMT. Long-term elasticity is interpreted as reflecting changes in the fuel economy of vehicles purchased and the long-term VMT changes generated by changes in where people live and work.

In January 2008 the Congressional Budget Office (CBO) reviewed the literature on fuel price elasticity and concluded:

> Estimates of the long-run elasticity of demand for gasoline indicate that a sustained increase of 10 percent in price eventually would reduce gasoline consumption by about 4 percent. That effect is as much as seven times larger than the

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[11] See http://www.epa.gov/fueleconomy/guzzler/index.htm for a gas guzzler tax program overview and lists of vehicles subject to the tax.

[12] This is similar to the "as tested" CAFE standard.

[13] Bastard (2010), p. 25. The tax and subsidy values have been adjusted in an effort to make the system more nearly revenue-neutral.

TABLE 6.1 Gasoline and Diesel Prices, Tax, and Percent Tax in 1990 and 2010

	France		Germany		Japan		United Kingdom		United States	
	1990	2010	1990	2010	1990	2010	1990	2010	1990	2010
Gasoline										
Total price	$5.60	$6.72	$4.09	$6.86	$4.87	$5.93	$4.35	$6.81	$2.08	$2.71
Tax	$3.97	$4.16	$2.56	$4.30	$2.29	$2.75	$2.63	$4.37	$0.56	$0.50
Percent tax	70.9%	61.9%	62.7%	62.7%	47.1%	46.3%	60.4%	64.2%	26.7%	18.2%
Diesel										
Total price	$2.66	$5.59	$4.06	$5.94	$2.61	$5.04	$3.05	$6.95	$1.48	$2.94
Tax	$1.67	$3.01	$2.30	$3.25	n/a	$1.66	$1.80	$4.39	$0.41	$0.53
Percent tax	62.8%	53.8%	56.6%	54.7%	n/a	32.9%	59.0%	63.1%	27.9%	17.9%

SOURCE: Data from Davis et al. (2011), Figures 10.2 and 10.3.

> estimated short-run response, but it would not be fully realized unless prices remained high long enough for the entire stock of passenger vehicles to be replaced by new vehicles purchased under the effect of higher gasoline prices—or about 15 years . . . consumers also might adjust to higher gasoline prices by moving or by changing jobs to reduce their commutes—actions they might take if the savings in transportation costs were sufficiently compelling. Those long-term effects would be in addition to consumption savings from short-run behavioral adjustments attributable to higher fuel prices. CBO (2008)

A 2009 study titled *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions* (Collaborative Strategies Group, 2009) modeled how much lower LDV fleet GHG emissions would be in 2050 (relative to 2005) if fuel prices or carbon taxes were used to boost U.S. motor fuel prices to West European levels. The elasticities used in the analysis were comparable to those cited in the 2008 CBO study. The reduction as a result of the improved fuel economy portion of the fuel price impact was 19 percent. The reduction as a result of the VMT impact portion was 8 percent (Collaborative Strategies Group, 2009 pp. B-15 and D-11).

Fuel taxes can also differ by fuel type, thereby influencing the choice of engine used to power a vehicle. In Europe, most vehicle models are available in both gasoline and diesel versions. The diesel versions cost more but deliver better fuel economy. France, in particular, taxes diesel at a much lower rate than gasoline—in 2010, the tax on diesel was $3.01/gal whereas the tax on gasoline was $4.16/gal. That differential has been credited with being an important factor in causing a rise in the diesel share of new automobiles in France from 2 percent in 1973 to 74 percent in 2007.

Fuel economy improvements reduce motor fuel tax revenues, all else equal, because under current law the amount of tax per gallon of fuel is constant. Inflation also erodes the real value of fuel tax revenues. Finally, substitution of hydrogen or electric vehicles for conventional vehicles would further diminish tax revenues unless those fuels were brought within the purview of the tax law. One solution would be to tax all forms of energy used by vehicles and index the motor fuel tax to inflation and also to the average energy efficiency of all vehicles on the road. For example, if total vehicle miles of travel per unit of energy increased by 3 percent from one year to the next, the tax in the following year would be increased by 3 percent. Such an indexed highway user fee on energy would maintain a constant tax rate per vehicle mile of travel while encouraging car buyers to purchase energy-efficient vehicles.

6.3.5 A Price Floor Target for Motor Fuels

A major impediment to investment in new alternative technologies, even when petroleum prices are high, is uncertainty about the future price path. Investors and consumers are less likely to invest in fuel-efficient technologies that require substantial up-front costs when they are uncertain about the payoffs from those investments. Prices of crude oil have been volatile in the past (Figure 6.2). In the late 1970s and early 1980s, the private and public sectors invested heavily in alternative fuels and AFVs, but many of the alternatives became uneconomic when prices of crude oil fell in the mid-1980s and remained low until the early 1990s.

One policy to stabilize the prices of petroleum-based fuels at a level that will help ensure a transition to more energy efficiency is through the use of a tax or surcharge on the price of oil that is applied only when oil prices fall below a specified target price. This surcharge would then be inversely related to the price of oil. For example, if the target price of oil with existing taxes is $90/bbl, and the price falls to $85/bbl over a specified period, the surtax would be $5/bbl, ensuring that the market price remains at $90/bbl. If the market price fell below $85/bbl, the surtax would increase, and if the market price rose above $90, then the surtax would be zero. The setting of the target price would be a policy choice made by Congress and the President and implemented in ways similar to other taxes on oil sales with the goal of stabilizing prices of petroleum-based fuels above a minimum price.

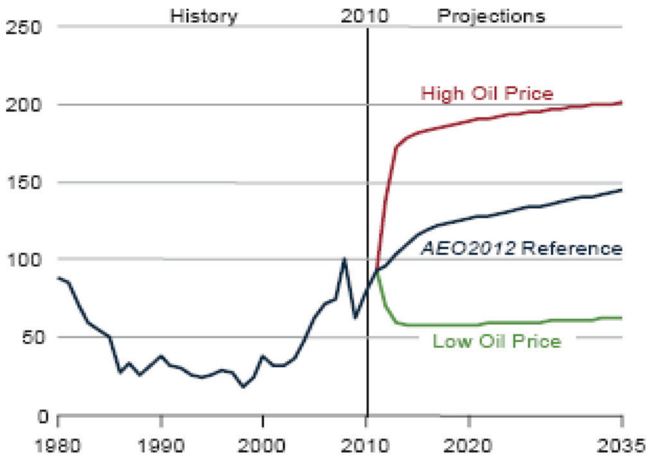

FIGURE 6.2 Actual average annual world oil prices from 1980 to 2010 and projected annual world oil prices from 2010 to 2035 under three different scenarios (in 2010 dollars per barrel). SOURCE: *Annual Energy Outlook 2012* (EIA, 2012).

Such a price floor or fuel price stabilization policy could be implemented on crude-oil sales in the United States as suggested above, or it could apply only to imported crude oil (Hubbard and Navarro, 2010). Borenstein (2008) shows how the concept of the oil price floor could be tied only to gasoline or other specific fuels that are derived from crude oil.

Revenues from any such surcharge would vary over time. They could be earmarked for use in current and proposed subsidies for alternative vehicles and AFVs, or used more broadly for tax or deficit reduction.

6.3.6 Policies to Change the Size and Weight Composition of the LDV Fleet

The average on-road fuel economy of the LDV fleet can also be changed by altering the fleet's composition. One example of the impact that such a change can have is the decline in U.S. on-road fleet average fuel economy due to the increase of trucks in the fleet mix between MY1980 and MY2004.[14] Policies could be designed to encourage or discourage such a shift.

An example of a policy change that discourages a shift in fleet mix is the 2007 legislation updating the CAFE program. Before then, CAFE standards were set for and had to be met by each of four fleets (U.S. cars, imported cars, U.S. trucks, and imported trucks) of each manufacturer selling vehicles in the United States. This approach permitted manufacturers to "downsize" or "upsize" their fleets as part of their CAFE fulfillment strategy and helped lead to the proliferation of trucks and SUVs in the fleet mix. The reform rule of 2006 restructured light-duty truck standards, basing them on a vehicle attribute, for which NHTSA selected footprint as discussed above. The EISA 2007 legislation authorized similar restructuring for all LDVs, and footprint-based standards have subsequently been promulgated for passenger cars and light trucks. Although the exact effect depends on the shape of the curve that maps vehicle footprint to regulatory targets for fuel economy, a general intent of this structure is that similarly sized vehicles would be required to achieve a similar increase in fuel economy. The regulatory curves are flattened at the extremes, to avoid standards that are too stringent for the smallest vehicles or standards that are too weak for the largest vehicles.

Designing and estimating the effects of such standards involve complex evaluations of many factors that influence vehicle design and engineering, customers' preferences, and automakers' product strategies. The analysis given in the EPA and NHTSA rulemaking studies concludes that the adopted footprint-based standards appropriately balance the many considerations that the agencies were required to weigh and does not provide any motivation for automakers to change their fleet mixes for CAFE purposes. Some have argued, though, that the chosen footprint curves inhibit downsizing as a cost-effective compliance strategy and may create an incentive to upsize the LDV fleet in a way that reduces fuel savings and GHG emissions reductions attributable to the standards (Whitefoot and Skerlos, 2012).

Other policies, such as the "Cash for Clunkers" program undertaken in 2009, have been designed to encourage consumers to dispose of lower-efficiency vehicles (which were then rendered inoperable) and replace them with higher-efficiency new vehicles, providing a stimulus to new-car sales. While the program was operating, it encouraged the purchase of fuel-efficient vehicles (Yacobucci and Canis, 2010). Because the program was temporary, most observers believe that it operated primarily to shift vehicle purchases in time rather than achieve any long-term impact on fleet composition. In a report published in October 2009, Edmunds.com estimated that of the nearly 690,000 new vehicles sold during the period the program was operating, only 125,000 of the sales were incremental (Edmunds.com, 2009).

6.3.7 Assessment of Vehicle Fuel Economy Improvement Strategies

The various policies described above each have demonstrated a potential to reduce the LDV fleet's average fuel consumption. It is generally agreed that the U.S. CAFE standards have been effective in stimulating the production and sale of more fuel-efficient vehicles (NRC, 2002). According to the EPA, the composite average LDV new-vehicle fuel economy (laboratory rated at 55 percent city driving and 45 percent highway driving) increased from 15.3 mpg (6.5 gal/100 mi) in MY1975 to 28.6 mpg (3.5 gal/100 mi) in MY2011, the latest year for which data have been published (EPA, 2010). Most of this increase occurred between

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[14] In 1980, "trucks" accounted for 16.5 percent of LDV production; by 2004 the truck share had reached 52.0 percent (EPA, 2010, Table 1, p. 7).

MY1978 and MY1988. The political acceptability and track record of the CAFE program have established it as a leading option among policies for meeting LDV petroleum use and GHG reduction goals. However, as discussed elsewhere in this chapter, a strict CAFE standard alone is not sufficient for meeting ambitious petroleum and GHG reduction goals because it fails to address issues of consumer motivation, travel demand, and other factors that shape the on-road fuel consumption of the LDV fleet.

Although there is less experience with their use, subsidies and taxes based on projected vehicle fuel consumption and imposed at the time of vehicle acquisition (feebates) could supplement (or, in principle, even substitute for) CAFE standards. So also could higher fuel taxes. Both types of policies have been shown to be effective in encouraging the purchase (or lease) of more fuel-efficient vehicles. However, the reluctance in the United States to raise taxes of any kind, consumers' undervaluation of fuel economy, and the level to which taxes would have to be raised to achieve results comparable to those seen with fuel economy standards, especially if supplemented by feebates, make their use problematic.

6.4 POLICIES TO REDUCE THE PETROLEUM USE IN OR GHG EMISSIONS IMPACTS OF FUEL

The second major factor influencing the LDV sector is petroleum's share of fuel use or the overall GHG emissions impact of supplying and using the fuel. Although numerous policies intended to reduce petroleum use by LDVs have been pursued over the years (e.g., the Energy Security Act of 1992 [96 P.L. 294], the Alternative Motor Fuels Act of 1988 [100 P.L. 494), the EPAct of 1992 and 2005 [109 P.L. 58], and the EISA of 2007 [110 P.L. 140] (DOE-EERE, 2011b), to date they have had little impact on the overwhelming dominance of petroleum-derived gasoline and diesel fuel. Nevertheless, many policy makers still show considerable interest in pursuing similar strategies for encouraging or mandating the use of biofuels, natural gas, hydrogen, electricity, or other non-petroleum fuels to power LDVs. Regulations, subsidies, various forms of tax incentives, and loan guarantees are now being used both in the United States and other countries to encourage the use of non-petroleum-based fuels and fuels that are expected to emit fewer GHGs. Fuel taxes and price floors on petroleum-based fuels also would discourage petroleum use.

Although the goals of reducing petroleum use and GHG emissions commonly are treated together (as in the case of the statement of task for this study; see Appendix A), the scientific, economic, and technical issues associated with these two goals are not identical. Each goal has its distinctive challenges associated with the design of fuels policies. Implementing any such policies requires appropriate metrics and the ability to track and measure effects throughout the fuel supply, distribution, and end-use systems that the policies seek to influence.

Measuring and tracking petroleum reduction require that the feedstocks used for producing fuel be quantified and reported. Given a legal definition of what qualifies as "non-petroleum" (e.g., as specified by AMFA [1988] and subsequent energy legislation), determination of the extent of petroleum reduction is conceptually straightforward. However, determining various fuels' net GHG emissions impacts is difficult, for several reasons:

- At least some of the GHG emissions or CO_2 uptake occurs upstream from the use of any fuel. For example, battery electric vehicles do not have tailpipe emissions, but the production of electricity to fuel the batteries may emit GHGs.
- The quantification of net CO_2 uptake, sequestration, and related emissions is uncertain in some cases. For example, the storage of carbon in soil by perennial bioenergy feedstocks depends on prior land condition and is difficult to estimate with high certainty.
- A significant portion of the GHG emissions impacts of all alternative fuels occurs outside the LDV sector. For example, the GHG emissions from electricity generation for powering battery electric vehicles or for producing hydrogen to power hydrogen fuel-cell vehicles occur in the power generation or hydrogen production sector. Therefore, the GHG emissions must be tracked in multiple sectors beyond the LDV sector.
- Biofuel-induced land-use changes and nitrous oxide flux from nitrogen fertilization could affect the net GHG emissions effects. Yet, the quantification of those net GHG emissions effects could be difficult.

6.4.1 Tax Incentives for Fuels and Their Infrastructure

During the energy crisis in the 1970s, policies were developed to support alternatives to petroleum ranging from synthetic fossil fuels to biofuels. The Energy Tax Act of 1978 (P.L. 95-618) introduced an excise tax exemption for gasohol. The exemption subsequently was extended and transformed into a tax credit for ethanol called the VEETC, a \$0.45/gal tax credit. Congress also approved a tariff on imported ethanol to foster domestic biofuel production. Both the VTEEC and the tariff expired at the end of 2011.

The EPAct of 2005 also established a tax credit of up to \$30,000 for the cost of fueling equipment for alternative fuels including hydrogen, natural gas, propane, electricity, E85, and diesel fuel blends containing at least 20 percent biodiesel.[15] Residential fueling equipment was eligible for a credit of up to \$1,000. The tax credits for hydrogen run through 2014; they expired at the end of 2011 for all other fueling equipment (DOE-EERE, 2011a).

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[15] California and a number of other states have policies for subsidizing a variety of alternative fuel vehicles (AFVs) and related infrastructure.

6.4.2 Fuel-Related Regulations

Traditional fuel regulations, as authorized under the original language of the CAA's Section 211, addressed fuel composition and its physical and chemical properties. These fuel-performance standards were based in principle on measurable fuel properties. Fuel suppliers could certify their products through laboratory testing or analytic methods based on physiochemical characteristics. Regulators could readily verify that standards were met by directly sampling fuel products, although this was rarely done. Because fuel additives and formulation requirements may not be finally incorporated into a consumer fuel until they are blended in at a distribution terminal, tanker truck, or even a fuel pump, the regulated entity may vary in fuel standards (40 CFR 80.2, Definitions).[16] The point of regulation is the point of finished fuel product distribution, which is where most fuel properties are determined.

Compliance with the complex model for gasoline emissions was a departure from this standard. There are a large number of fuel parameter combinations that could meet the requirements for compliance, and compliance was referenced to the base fuel of each individual fuel supplier. Compliance was determined before the fuel left the production facility. Once the fuel was distributed and comingled with other fuels that complied at production, it was no longer possible to determine compliance at the final point of distribution.

As energy policy considerations came into play, regulations were designed to stipulate the use of certain fuels derived from specified non-petroleum feedstocks. Thus, fuel regulations developed for energy policy take the form of a legal requirement to supply a certain amount of a fuel manufactured from particular resources. Others take the form of a requirement to supply a minimum percentage of a group of fuels derived from desired sources or to supply a mix of fuels that on average meet requirements for being derived from desired sources. Such is the case for the amended Renewable Fuel Standard (RFS2) in the EISA. An approach generalized to require a mix of unspecified fuels that meet specified average net GHG emissions over their life cycle is known as a Low-Carbon Fuel Standard (LCFS), and such a standard has been established in California.

6.4.3 Renewable Fuel Standard[17]

RFS2 was intended to move the United States "toward greater energy independence and security" and to "increase the production of clean renewable fuels" (110 P.L. 140). RFS2 is actually a collection of mandates for fuel providers to supply categories of renewable fuels defined by their feedstock type and life-cycle GHG emissions (Box 6.2). The volume mandate for the "renewable fuel" category has been met by corn-grain ethanol and is expected to be met up to 2022 (NRC, 2011). Production capacity is available for meeting the volume mandate for biomass-based diesel. However, commercial production of cellulosic biofuels has fallen far short of the volume for that category mandated by EISA. Indeed no compliance-tracking renewable identification numbers (RINs) had been generated for cellulosic biofuels as of April 2012 (EPA, 2012a).[18]

EISA gives EPA the right to waive or defer enforcement of RFS2 under a variety of circumstances. For example, RFS2 can be waived if sufficient biofuels are not likely to be produced for blending or if its enforcement has been deemed to cause economic dislocation (NRC, 2011). For example, the governors of nine states, 26 members of the U.S. Senate, and 156 members of the U.S. House of Representatives petitioned EPA to grant the RFS waiver, citing the effects of the 2012 drought on U.S. food and feed prices as the reason for potential economic dislocation. The EPA has been exercising its discretion to reduce the level of cellulosic biofuels required in RFS2. Specifically, the EPA reduced the mandate for cellulosic biofuels by 93 percent in 2010 (from 100 million to 6.5 million gallons), by 97 percent in 2011 (from 250 million to 6.6 million gallons), and by 98 percent for 2012 (from 500 million to 10.5 million gallons) (EPA, 2012b). When there is a waiver, blenders are permitted to buy RINs from EPA instead of actually purchasing cellulosic biofuels. There also is a clause that allows blenders to buy RINs from EPA even if cellulosic biofuels are available but substantially more expensive than petroleum-based fuels (Thompson et al., 2010; NRC, 2011). Although the intent was to protect consumers from high prices relative to gasoline, the clause effectively eliminates a guaranteed demand for cellulosic biofuels. The potential waiver and clause regarding the purchase of RINs reduce the incentive for the major fuel producers to develop and deploy technology for producing cellulosic biofuels, particularly when large financial investments and risks are involved. But without the waiver, blenders are required to purchase fuel that is not being made; their only option is to buy RINs. The cost of cellulosic fuels has not come down as some had hoped. The combination of high cost, the potential waiver, and the clause described above have undermined the effectiveness of RFS2 in driving an increase in cellulosic biofuels.

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[16] Code of Federal Regulations, Title 40, Part 80, "Regulation of Fuels and Fuel Additives," Definitions section; available at www.gpoaccess.gov/cfr/index.html.

[17] This description is taken from EPA's website.

[18] "The Renewable Identification Number (RIN) system was developed by the EPA to ensure compliance with RFS2 mandates. A RIN is a 38-character numeric code that corresponds to a volume of renewable fuel produced in or imported to the United States. RINs are generated by the producer or importer of the renewable fuel. RINs must remain with the renewable fuel as the renewable fuel moves through the distribution system and as ownership changes. Once the renewable fuel is blended into motor vehicle fuel, the RIN is no longer required to remain with the renewable fuel. Instead, the RIN may be separated from the renewable fuel and then can be used for compliance, held for future compliance, or traded" (McPhail et al., 2011, p. 5).

BOX 6.2
Life-Cycle Assessment for Greenhouse Gas Emissions

Life-cycle assessment (LCA) is a tool available for the accounting of net greenhouse gas (GHG) emissions effects of different fuel pathways. However, the use of LCA to determine policy compliance is a marked departure from traditional approaches to fuels regulation, which prior to the RFS had always been based on physiochemical fuel properties. Standards based on a fuel's physiochemical properties are enforceable through measurement or measurement-based analytic methods that allow verifiable assurance of fuel providers' compliance. However, fuel property standards are not adequate for regulating the GHG emissions associated with both production and use of a fuel. Fuel property standards cannot account for upstream emissions associated with any fuel. Therefore, LCA is used to assess the GHG emissions impacts of fuels. However, GHG emissions occur in multiple sectors in geographically dispersed locations and over multiple periods of time. For example, for biofuels, CO_2 uptake by biomass and sequestration in soil or GHG emissions from indirect land-use changes occur remotely from locations of fuel use in the transportation sector. Thus, accounting for life-cycle emissions is more complicated and uncertain than it is for direct emissions (NRC, 2011).

Some members of the committee believe that a problem with using LCA in policy regulation is a misplaced burden of proof (DeCicco, 2012) because some of the CO_2 sequestration and emissions occur outside the LDV sector and are not under the control of fuel producers, fuel retailers, or fuel users. Others believe that it is appropriate to hold fuel providers responsible for the upstream emissions of their products. The parties that are responsible for the direct and indirect emissions from all the different parts of the biofuel supply chain have not been clearly established. If the United States is to limit the GHG emissions impacts of LDVs and their associated fuel supply systems (as opposed to their direct tailpipe emissions only), then policies are needed to address the GHG emissions from other sectors upstream from fuel use. Although GHG emissions from the transportation sector could be reduced in the United States by RFS2, the policy may not contribute to reducing global GHG emissions.

RFS2 requires EPA to determine whether the four types of renewable fuel meet their respective GHG thresholds. Although the intent was to ensure that biofuels have lower GHG emissions impacts compared to petroleum-based fuels, whether the policy will actually contribute to a reduction in GHG emissions is uncertain. The NRC report *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy* concluded that "RFS2 may be an ineffective policy for reducing GHG emissions because the effect of biofuels on GHG emissions depends on how the biofuels are produced and what land-use or land-cover changes occur in the process" (NRC, 2011; p. 2-4). The same physical fuel can have widely different life-cycle GHG emissions depending on numerous factors, including the feedstock used (e.g., corn stover or switchgrass), the management practices used to produce the feedstock (e.g., nitrogen fertilization during biomass growth), the energy source used in the biorefinery (e.g., coal or renewable electricity), and whether any indirect land-use changes were incurred as a result of feedstock production. For example, the use of crop or forest residues for feedstock is less likely to cause indirect land-use changes than is the use of planted crops. Moreover, indirect land-use changes as a result of bioenergy feedstock production and the associated GHG impacts are difficult to ascertain.

6.4.4 Possible Alternative to RFS2

Because GHG sources and sinks are dispersed across sectors (agricultural, forestry, and industrial) and international borders, some committee members believe that policies that target them at the location where they occur are likely to be much more effective than RFS2 in reducing GHG emissions impacts. RFS2 includes a GHG accounting system that can account for upstream emissions. This system requires an elaborate tracking mechanism and a combination of real-world measurement and estimation of GHG emissions at each source and sink along the supply chain to verify overall claimed benefits from the production and transport of the biomass through conversion and distribution of the final products.

6.4.5 California's Low Carbon Fuel Standard

A regulatory effort to encourage the use of alternative fuels, with the specific intent of lowering GHG emissions, is California's LCFS. On January 18, 2007, California's then-governor issued Executive Order S-1-07 that called for a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020. The California Air Resources Board developed regulations to implement the order, approving them in April 2009. After delays due to litigation the regulations were promulgated on June 4, 2012, under an April 2012 court order permitting the promulgation to occur pending the results of an appeal that was still underway at the time of this writing.

The LCFS uses life-cycle assessment (LCA) rather than direct measurement of fuel properties to determine compliance. It applies to essentially all transportation fuel used in the state. Regulated parties are defined broadly as fuel producers and importers and some owners of alternative fuels or alternative fuel sources. The regulation defines a carbon intensity (CI)[19] metric based on LCA. Fuel suppliers are required to progressively lower the average CI of the fuel they supply. The targeted GHG-emission reduction is 10 percent in 2020 compared to the average baseline of transportation fuels in 2010. The LCFS assigns a CI to different types of biofuel (e.g., corn-grain ethanol produced via different pathways with different types of energy input gets different scores) and a CI for land-use change and other indirect GHG effects. However, the actual GHG effects from land-use change and other indirect effects could span a wide range (Mullins et al., 2010; Plevin et al., 2010). Given the large uncertainties, the extent to which LCFS actually contributes to reducing net GHG emissions is unclear. One committee member considers that the uncertainties in LCA are such that one cannot have confidence in the efficacy of an LCFS or other policies using LCA to ensure reductions of GHG emissions from fuels. As is the case with RFS2, fuel providers are held accountable for upstream GHG emissions and GHG emissions from indirect effects. They do not control these effects but can mitigate them by their choice of the source of their fuel supply.[20]

LCFS allows fuel providers to petition for individualized CI score. LCFS proponents view such provisions as beneficial for fostering innovation in low-emission fuel production. For example, some ethanol producers could sequester their CO_2 emissions, account for them, and seek credit for these reductions under the LCFS. Similarly, oil companies practicing enhanced oil recovery could seek credits for the portion of the injected CO_2 that remains in the water phase of the oil well and the portion that is dissolved in the unrecovered oil.

6.5 POLICIES TO IMPACT VEHICLE MILES TRAVELED

Since 1970, increases in U.S. LDV vehicle miles traveled have more than offset improvements in LDV on-road fleet fuel economy (see Figure 6.1). As a result, LDV petroleum use and CO_2 emissions have increased over the period. With VMT being such a driver of increased petroleum use and CO_2 emissions, it is natural that attention has been devoted to finding ways of reducing its rate of growth—or even its absolute total. This section reviews the principal policies that have been examined and what is known about their likely impact.

6.5.1 Historical and Projected Future Growth in LDV VMT

Between 1970 and 2005, VMT in the U.S. LDV fleet grew by an average annual rate of 2.8 percent. This rate of growth is not expected to continue. Indeed, the average annual rate of VMT growth from LDVs projected by the Energy Information Administration's (EIA) *Annual Energy Outlook* (EIA, 2011) for the period 2010 to 2035 is only about 60 percent of the average rate experienced between 1970 and 2007, the peak year prior to the recent economic recession.

But VMT is still projected to grow. Indeed, if the 1.49 percent annual growth rate of VMT over the last 5 years of EIA's projection period is assumed to be realized as well during the 2035-2050 period, VMT in 2050 will be 5.0 trillion—an 85 percent increase relative to its 2010 level.[21]

6.5.2 Reducing the Rate of Growth of VMT by Increasing Urban Residential Density

The relationships among household location, workplace location, trip-making activity, and LDV travel have been subjects of research and policy debate for many years. These relationships have been difficult to establish for many reasons, including the problem of controlling for variables such as self-selection bias as households locate in places that best suit their travel needs, preferences, and capabilities. However, there is general agreement that higher urban density is associated with less driving. The important issues are (1) the magnitude of this relationship and (2) the extent to which VMT might be altered by changes in urban density.

An NRC study analyzed in great detail the impact of compact development (another term for increased urban density) on motorized travel, energy use, and CO_2 emissions. The principal findings of the 2009 study can be summarized as follows:

- Developing more compactly, that is, at higher residential and employment densities, is likely to reduce VMT.
- Doubling residential density across an individual metropolitan area might lower household VMT by about 5 to 12 percent, and perhaps by as much as 25 percent, if coupled with higher employment concentrations, significant public transit improvements, mixed uses, and other supportive demand management measures[22] (NRC, 2009, pp. 2-6).

The 2009 analysis suggests that reductions in national VMT resulting from compact, mixed-use development

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[19] Carbon intensity as defined in the LCFS is equivalent to life-cycle greenhouse gas emissions.

[20] In 2012, California was enjoined from enforcing the Low Carbon Fuel Standard because of a December 29, 2011, decision by the Federal Eastern District Court of California in the case of *Rocky Mountain Farmers Union vs. Goldstene*. The state is appealing the decision to the Ninth Circuit Court of Appeals, which lifted the lower court's injunction on April 23 and thereby allowed the state to proceed with LCFS implementation pending appeal (CARB, 2012).

[21] This is the number used in the business-as-usual and reference cases and in most of the policy simulations in this report.

[22] The 2009 committee commented on its second conclusion as follows: "Doubling residential density alone without also increasing other variables, such as the amount of mixed uses and the quality and accessibility of transit, will not bring about a significant change in travel" (NRC, 2009, p. 89).

might range from less than 1 percent to 11 percent. The high estimate would require 75 percent of new development to be built at double the density of existing development, a significant departure from the declining densities recorded in most urban areas over the past 30 years. The study emphasizes that increasing densities and mixing land uses may be more achievable in some metropolitan areas than others. Metropolitan areas differ a great deal in their geographic characteristics, land area, historical growth patterns, economic conditions, and local zoning and land-use controls. Policies that affect land use are local in the United States and in some areas in the past have led to decreasing density as urban areas have expanded. In others, strong regional authority with a commitment to more compact land use has increased density through land-use policy.

The present committee concluded that the likely changes in VMT as a result of changes in residential density would be small in the aggregate.

6.5.3 Reducing the Rate of Growth of VMT Through the Use of Pricing Strategies

Many strategies in addition to those encouraging increased residential density have been suggested as having the potential to reduce the rate of growth of VMT. The 2009 *Moving Cooler* study (Collaborative Strategies Group, LLC. 2009) mentioned above examined a number of pricing strategies, including congestion pricing, intercity tolls, pay as you drive (PAYD) insurance, a VMT tax, and a gas or carbon tax. Each of these pricing measures produced a reduction of 1 percent or greater in 2050 urban VMT under all levels of policy intensity studied—extended current practice, aggressive implementation, and maximum implementation. Indeed, the VMT impact of a fee per mile traveled at maximum implementation was estimated to reduce 2050 urban VMT by about 8 percent.[23]

6.5.4 Reducing the Rate of Growth of VMT Through Other Policies

Moving Cooler (Collaborative Strategies Group, LLC. 2009) also examined a range of additional policies deemed to have the potential to reduce the future rate of VMT growth. As in the case with pricing strategies, each of these other policies was evaluated at three levels of implementation. Three of the non-pricing strategies were estimated to have a 1 percent or greater impact on 2050 urban VMT with expanded current practice; four had a 1 percent or greater impact with practice more aggressive than current practice; and five had an impact of 1 percent or greater with maximum implementation. Although some of these strategies may be additive, many are not. Also, some strategies (such as the transit strategies, pedestrian strategies, and certain of the employer-based commute strategies) may already be reflected in the density-based VMT impacts reported earlier in this chapter. Indeed, the 25 percent reduction in VMT cited in NRC (2009) as a possible upper bound due to higher density was generated by a combination of VMT-related policies, not merely increased density.

6.5.5 Summary of the Impact of Policies to Reduce the Rate of Growth of VMT

Policies designed to reduce the rate of growth of VMT are likely to have limited impact compared with policies targeting vehicle efficiency and new energy sources. Even the extreme reorganization of national economic activity needed to produce the higher level of urban density examined in NRC (2009) would yield only an 11 percent reduction in VMT. And it should be remembered that the various VMT-related policies are not additive. Nevertheless, this limited VMT impact should not lead to the inference that such policies might not be valuable for other reasons.

6.5.6 Policies to Improve the Efficiency of Operation of the LDV Transport Network

As noted above, there has been considerable recent interest in the extent to which policies designed to improve the operating efficiency of the LDV transport network might also serve to reduce GHG emissions or petroleum use. Examples of such policies are eco-driving programs; ramp metering; variable message signs; active traffic, integrated corridor, incident, road weather, and signal control management; traveler information; and vehicle infrastructure integration. Many of these policies focus on reducing congestion to help even out vehicle speeds and reduce time spent stopped in traffic. Others provide drivers with the knowledge and information needed to learn to drive their existing vehicles using less fuel.

There is no dispute that drivers can, if they are careful and attentive, significantly improve the fuel economy they experience on the road. There also is no dispute that congested conditions waste fuel as well as drivers' time. The question is how widespread the use of eco-driving or the implementation of technologies that have a potential to reduce congestion (e.g., vehicle-to-vehicle communications, also known as telematics) become and how great the aggregate impact of such policies and technologies might be at the national level.

The challenge in developing such estimates is somewhat similar to the challenge of estimating the impact of increased urban density on VMT growth. In both cases, examples showing major potential, and sometimes actual, improvements in specific local situations can be cited. But how generalizable are these local results either to other localities

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[23] "Maximum implementation" is a \$0.12/mi fee, representing the increment needed to represent Western European motor fuel tax levels. It was derived based on an additional tax of approximately \$4/gal on an approximate average on-road 33 mpg.

or, more importantly, to the national level? And are there factors that can be expected to offset these improvements to some degree over time?

Little research has been done to address these issues. Indeed, the only estimate of the possible national impact over time that the committee is aware of appears in the *Moving Cooler* report discussed above.

That report counts as "benefits" only the fuel savings and associated GHG emissions reductions resulting from the various measures to improve the operational efficiency of the road transport network.[24] It subtracts from these benefits an amount that reflects the VMT increase projected to result from reduced congestion.[25] *Moving Cooler* also takes into account the rate and extent of deployment of these strategies (Collaborative Strategies Group, 2009). Even at maximum deployment, the only strategy that reduces GHG emissions and fuel consumption by more than 0.5 percent as of 2050 is ecodriving, which yields a 4 percent reduction in GHG in that year.[26]

Moving Cooler acknowledges that these estimates are rather rough and might be greater if deployment of the strategies occurs sooner, of development is more widespread, or if the strategies themselves are more effective than they now appear to be. Clearly, there is much need for additional research on this topic.

6.6 POLICIES IMPACTING THE INNOVATION PROCESS

Identification, development, and commercialization of technologies that yield vehicles that are more efficient than current vehicles, AFVs, fuels from non-petroleum resources, fuel production systems with reduced GHG emissions, and, in some cases, even the means of reducing the rate of VMT growth often stem from research undertaken years before the technologies appear in the market. This section examines the different stages of the innovation process to address the questions about the role of government in this process.

There is no universally agreed-upon taxonomy for the stages of the innovation process, but one common framework divides the process into four stages (NSF, 2007):

1. *Research*, or "systematic study directed toward fuller knowledge or understanding." Research may be basic or applied. Basic research is directed toward the "fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind." Applied research is directed toward "determining the means by which a recognized and specific need may be met" (NSF, 2007; p. 1).
2. *Development*, which takes the knowledge produced in research and systematically applies it toward the production of useful materials, devices, and systems or methods to meet specific requirements, often culminating in prototypes.
3. *Demonstration*, which tests the feasibility of the developed technology at an appropriate scale to identify all significant impediments to commercial success.
4. *Deployment*, in which the technology becomes widely used.

The need for government intervention is most widely accepted for the first two of these four stages: research and development (R&D). R&D builds the nation's intellectual capability to address energy problems. Even in the presence of strong intellectual property protection, private businesses generally cannot capture all of the benefits generated by their R&D investments, especially any investments that they might make in basic research. Because of this "spillover effect," private investment in R&D falls short of the socially optimal amount, thereby justifying public support.

There is an even stronger case to be made for publicly funded R&D to reduce greenhouse gas emissions and to displace petroleum use. The production and use of petroleum-derived energy generate negative environmental externalities and impose national security costs, neither of which is fully reflected in market prices. These social concerns compound the insufficient motivation for private firms to invest in R&D aimed at achieving these particular objectives.

Although this committee is not in a position to recommend specific levels of government R&D spending to advance vehicle and fuel technology, one insight from its analysis is that maintaining a diverse R&D portfolio is appropriate given the nature of the challenge. The committee's scenarios demonstrate that several pathways involving combinations of advanced vehicle and fuel technologies have the potential to achieve the goals of an 80 percent reduction in petroleum use and GHG emissions from LDVs. R&D critical to success for many key vehicle and fuel innovations includes:

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[24] Estimates given in *Moving Cooler* (Collaborative Strategies Group, 2009) cover all road vehicle traffic, not merely LDVs. Other benefits that are not counted by *Moving Cooler* include time savings that may result from these measures.

[25] This "induced driving" effect is used by opponents of building more roads to argue that doing so only causes more driving. Using Federal Highway Administration models, *Moving Cooler* estimates that a systemwide average reduction in delay of 1 hr/1000 VMT in the absence of induced demand results in a systemwide increase in VMT of 2.13 percent. This increase in VMT results in a proportionate increase in fuel consumption and GHG emissions. This increase will be less in the short run than in the long run. *Moving Cooler* adjusts GHG emissions from increased VMT in the initial year of strategy deployment by (2.13 percent × 0.5), ramping this increase to the full 2.13 percent after 10 years (Collaborative Strategies Group, 2009, p. B-88).

[26] Some of these strategies might be somewhat additive, but it does not appear reasonable to claim that they are totally additive. Even if they were, the impact of the policies other than ecodriving would total only 1.4 percent (Collaborative Strategies Group, 2009, p. D-12).

- Low-cost, conductive, chemically stable plate materials for fuel cells;
- New, durable, low-cost membrane materials for the fuel cell stack and batteries;
- New catalyst structures that increase and maintain the effective surface area of chemically active materials and reduce the use of precious metals;
- New processing techniques for catalyst substrates, impregnation, and integration with layered materials;
- Energy storage beyond lithium-ion batteries;
- Reduced cost of carbon fiber and alternatives to polyacrolyonitrile as feedstock;
- Replacements for rare-earths in motors;
- Waste heat recovery; and
- "Smart car" technology.

Key fuel technologies include:

- "Drop-in" biofuels with low net GHG emissions;
- Carbon capture and storage; and
- Advanced hydrogen production technologies with low net GHG emissions.

These two lists may not be exhaustive over the time horizon examined; rather, they represent options already included in DOE's R&D portfolio. All of the fuel options entail combinations of new energy resources or carbon capture and storage technologies sufficient to deliver biofuels or other synthetic fuels, electricity, hydrogen, or combinations thereof with low net GHG emissions impacts. It is unclear which pathway is most likely to succeed, because each depends on technology success, cost reduction, consumer acceptance, and public policies.

6.6.1 Demonstration

Once a technology moves beyond research and development, the case for government support becomes more controversial. Consider the case of federal funding of demonstration projects. Suppose that R&D has yielded a new way of producing a fuel for LDVs. The R&D process may have shown that the technology works in a laboratory, but it does not demonstrate system integration in a production setting that might be scaled to a commercial level.[27] Before private industry will invest the large sums required to construct large numbers of commercial-scale plants employing such technology, someone must construct a first-of-a-kind commercial-scale plant. Prior to that, there may be a need to test and refine the workability of the technology in a production-like setting through the construction and operation of a pilot plant at less-than-commercial scale. Industry also may be unwilling to shoulder those costs. The cost of producing fuel in a first-of-a-kind commercial-scale plant likely will not be as low as it might become, because the first-of-a-kind commercial-scale plant will not have the benefit of the "learning-by-doing" that can lower construction and operating costs. But without this step, full-scale commercialization will not occur.

If the technology is protected by strong patents or can be kept secret, and if the price that the firm constructing a first-of-a-kind commercial-scale plant can expect to receive for output from the plant reflects nearly all of the benefits that the technology creates, a private firm may run the risk of constructing this demonstration plant on its own. But if the developer of the technology cannot protect it from being easily appropriated by others, or if a significant share of the benefits cannot be captured in the price that the output of the plant will sell for, a private firm is not likely to be willing to take this step. In such cases, the first-of-a-kind commercial-scale plant may not be built without some form of government financial assistance. However, if the eventual business case for the technology relative to competing options (including potential progress in an incumbent technology) is weak, then even a government-financed first-of-a-kind demonstration may not lead to the scale-up to multiple or larger plants needed for commercial success. (However, some of the government policies discussed above in this chapter, such as a carbon tax or a price floor on oil, could improve the business case for certain alternative technologies.)

Vehicles pose a different demonstration issue. Manufacturers commonly create demonstration fleets to generate information on the in-use performance of vehicles using new powertrain systems. Examples of demonstration fleets include the General Motors EV1 and Equinox hydrogen fuel cell vehicles, Honda FCX Clarity, Audi A3 E-tron, and the Mini E. In these cases, only a limited number of vehicles have been produced. They were made available only to screened applicants, and ownership of the vehicle remains with the manufacturer.

Circumstances may dictate that government must directly participate in the demonstration project. In the case of the DOE's National Fuel Cell Vehicle Learning Demonstration Project, the primary goal was to validate vehicle and infrastructure systems using hydrogen as a transportation fuel for LDVs under real-world conditions using multiple sites, varying climates, and a variety of sources for hydrogen.[28] Specific objectives included validating hydrogen vehicles with more than a 250-mile range, 2,000-hour fuel cell durability, and hydrogen production costs of $3 per gallon of gasoline equivalent. The project was structured around a highly collaborative relationship with four industry teams—Chevron/Hyundai-Kia, Daimler/BP, Ford/BP, and GM/Shell—with the National Renewable Energy Laboratory (NREL) collecting and analyzing the data and publishing results. A

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[27] A pilot facility is a form of demonstration that integrates technologies developed in the laboratory into a production system. The pilot demonstration is a step toward commercial design.

[28] This description is taken from Wipke et al. (2010).

total of 140 fuel cell vehicles, covering both Generation 1 and Generation 2 technology, were deployed over the course of the project. Twenty refueling stations, utilizing four different types of refueling technology, were deployed. The geographic regions covered were the San Francisco to Sacramento region, the Los Angeles metro area, the Detroit metro area, the Washington, D.C., to New York region, and the Orlando metro area.

The project established specific goals for many of the technical and operating questions and periodically reported progress toward meeting these goals. A detailed summary of the project's results through 2009, identifying which goals had been met and which goals still needed to be met, was published in 2010. Some teams ended their participation in 2009, but some continued at least through most of 2011. At an update made available in early 2012, NREL reported that through the third quarter of 2011, vehicles assigned to the project had accumulated a total of 154,000 operating hours and had traveled a total of 3.6 million vehicle-miles (NREL, 2012).

What seems to have made this demonstration project successful was its careful design that involved the coordination of a simultaneous demonstration of vehicles and fueling infrastructure, its focus on measurable goals that were critical to the eventual success of hydrogen-electric vehicles, mandatory reporting of detailed performance data including safety to establish expected baselines for commercialization, and its use of paired teams of vehicle manufacturer and fuel manufacturer, with the government playing a facilitating and coordinating role.

6.6.2 Deployment

The next step after demonstration is deployment—the roll out of a fully demonstrated technology with all of the technical and economic aspects as fully defined as possible. This is likely to be particularly challenging in the case of vehicles using non-liquid fuels, such as grid-connected-electric, natural gas, or hydrogen fuel cell vehicles, Even after successful completion of the demonstration phase, potential vehicle purchasers would need to be convinced that the technology is reliable and that the form of energy it requires will be available, while energy suppliers and vehicle manufacturers would need to be convinced that the vehicle/fuel system would be purchased by consumers in increasing volumes within timeframes relevant to major private investment planning. Cost reduction through learning-by-doing and by increasing sales volumes to achieve economy of scale likely would be necessary to ensure availability of a range of vehicle makes and models to consumers. Refueling infrastructure also would have to be widely enough available to sustain an expanding market.

The analysis in Chapter 5 illustrates that the timing of deployment is critical if the 2050 petroleum use and GHG reduction goals are to be achieved. Because of the long lifetime of the LDV fleet, vehicles incorporating the sorts of technologies described in Chapter 2 would have to be in the market in substantial quantities by about 2035. If these vehicles require a new fuel infrastructure, enough of it would have to be in place even prior to this date to quell vehicle owners' anxieties about fuel availability. The Chapter 5 analyses suggest that transitions in energy resource and supply sectors or to alternative fuels, AFVs, or any combinations would have to be forced more rapidly than would occur through private market forces alone if the goals are to be achieved by 2050. Therefore, financial inducement from either private or public resources will be required.

The condition for private investment in deployment is that the technology is so promising that the potential investor would prefer it over other opportunities. Because of the long timeframe and uncertain outcome, potential private investors will require a high rate of return on that investment and will limit the amount they will invest to a level that does not endanger their long-term financial viability. The analyses in Chapter 5 suggest that deployment of alternative LDV and fuel technologies will in some cases be too large, last too long, and be too uncertain for a private entity to support financially. Further, the modeling shows that a substantial part of the return on the investment will accrue to society at large rather than to the private investor.

Policy-driven deployment is likely to be necessary to encourage and support a new technology through the early phases of market introduction, particularly if the success of the investment depends heavily on societal benefits. For AFV systems, publicly funded deployment encouraged by public policy might be especially important for addressing two major barriers:

- The scale-related cost problem associated with the fact that new vehicle-fuel systems lack sufficient economies of scale during the early stages of commercialization, and
- The coordination of commercial deployment of AFVs with the fueling infrastructure for those vehicles.

Nevertheless, given the uncertainties involved, technology-specific deployment programs may not be needed. If such programs are needed, several general principles should be followed:

- The deployment effort should be undergirded by and based on a long-term, substantial market signal to focus and drive reducing petroleum use and GHG emissions. An example would be a carbon tax or an equivalent means of setting costs for carbon GHG emissions.
- The cost of deployment would have to be known and the amount be acceptable.
- The time period over which any public investment is provided would have to be limited, and a technical

agency would be used to develop metrics to assess progress and guide adjustments by policy makers based on the achieved results, including building on effective activities and terminating activities that are ineffective or are overcome by events.

- A condition of public investment needs to be the presence of one or more legally committed private partners obligated to make a substantial investment so as to have a stake in the success of the technology deployment.

The government has tools in addition to direct investment that it can use to ease the investment hurdle for private capital. These could include loan guarantees to lower the rate of interest paid by the investor for the necessary private capital and direct loans to the investor at less than market rates. The government can also use mandates. Government mandates that set goals that are truly technology neutral tend to be attractive because they allow industry rather than the government to select the most promising means to meet the requirement. However, loan guarantees, loans and below-market interest rates, and mandates all share the disadvantage that they tend to hide the true cost of the government support.

A strongly mitigating factor against government involvement in technology-specific deployment is that there is little or no successful experience to guide the selection of policies and tactics for such actions for vehicles and fuel technologies. One relevant precedent is the successful reduction of air pollutants from LDVs. The government's effort there was generally directed at the outcome rather than a particular achievement path.

The route to achieving the 2050 goals is not clear, and so the government's approach to pursue these goals has to be flexible and adaptive. The government must be able to assess candidate activities, select only those with a high chance of success, accept some risk because success is not guaranteed in every case, and be robust enough to survive when approaches initially chosen fail. The government needs to make unbiased and prompt assessments of progress and act swiftly to modify ineffective efforts and terminate those that are failing.

6.7 POLICIES IMPACTING PUBLIC SUPPORT

Fostering public understanding of the rationale underpinning various policy decisions, regulatory actions, and vehicle and fuel technologies designed to achieve the nation's GHG and petroleum reduction goals for the LDV fleet is critical to achieving public support of same.

It has been demonstrated that proper dissemination of information that increases consumers' awareness of and knowledge about a particular policy or program—alone or in concert with incentives—can have a more permanent impact on consumers' behavior than do incentive programs alone (Hopper and Nielsen, 1991; Iyer and Kashhyap, 2007).

Regarding the adoption of hybrid vehicles, it has been demonstrated that consumers today have little knowledge of the technology and limited knowledge of the potential benefits of the technology (e.g., roominess, power, and quiet operation) beyond the financial and environmental benefits (Ozaki and Sevastyanova, 2011).

In addition, financial and other incentives unsupported by effective public information programs do little to increase the number of people performing the behavior being incentivized and typically have the most influence on those already disposed to accept the policies and goals being promulgated, whereas public information programs have the potential of helping consumers form positive opinions about the recommended goals and policies—especially those who held no opinion, and even those who were opposed to such goals and policies, before being exposed to the information campaign (Allen et al., 1993; Ditter et al., 2005).

Overcoming the lack of knowledge about the need to achieve the recommended goals also is critical. Although some number of consumers will respond solely to policies providing financial benefit for modifying their driving habits to lower VMT and/or facilitate their purchase of low-emitting and AFVs, it will be decades, if ever, before such vehicles demonstrate performance and cost-of-ownership characteristics that make them clearly competitive with conventional vehicles. In their 2004 study of the impact of energy-efficiency audits on the adoption by industry of efficiency technologies such as energy-efficient lighting, heating, and cooling systems, Anderson and Newell (2004, p. 2) found that "access to more accurate performance information can reduce the uncertainty and risk associated with adopting technologies that are new, or that receive differing reviews from equipment vendors, utilities, or consultants." The Washington State Department of Transportation, which has a long history of successful public transit and VMT reduction programs, has found that public education "is a vital element" in its transportation demand management projects (McBryan et al., 2000).

6.8 ADAPTIVE POLICIES

As discussed throughout this report, many uncertainties surround advanced LDV, fuel, and energy supply technologies. Today's knowledge of the feasibility, scalability, costs, and benefits associated with the options analyzed in this report is insufficient to craft policies framed around any specific vehicle-fuel systems. Analysis performed today can be suggestive but is never dispositive about what technologies will succeed in the future. Neither can the market responses of the diverse actors whose decisions determine both technology adoption and the real-world impacts of its use be predicted with much certainty. As Dwight D. Eisenhower remarked, "Plans are nothing; planning is everything." Policy makers face a need to design measures that can be modified as new information becomes available while maintaining a focus on meeting the goals of the policy. Although it addresses a different issue, a RAND (RAND Europe, 1997, p. 2) study summarizes this sensibility by saying that "a realistic approach to the formulation of policy should explicitly confront the fact that policy will be adjusted as the world changes and as new information becomes available." An example of such an adaptive policy is provided in Chapter 5 (see Section 5.6, "Adapting Policy to Changes in Technology"). In that example, a mid-course change in policy was made as a result of an unanticipated improvement in one vehicle technology or fuel type, and the study goals were met.

In considering what such an adaptive policy framework might look like, it is important that it not be trivialized to a mere exhortation that "policy makers should adapt." Policy makers adapt all the time. Although the criticism, "America lacks an energy policy," is often heard, the country in fact has as energy policy that has developed over time, including evolving measures to address transportation energy use. Congress and successive administrations have adapted laws, regulations, and other programs to new conditions and new information, satisfying different needs and interests to different degrees (perhaps leaving some unsatisfied). Vehicle efficiency standards have been modified over the years depending on the public priority placed on petroleum conservation and more recently coordinated with CAA-authorized GHG emissions standards in response to climate concerns.

The track record of the existing approach to transportation energy policy is decidedly mixed. CAFE standards have helped to limit growth in oil demand and GHG emissions, but at uneven rates over the years. Whatever learning may have been achieved, in the United States alternative fuel and vehicle technologies have had little impact on the sector's petroleum dependence and no measurable benefit on its net GHG emissions intensity (which may in fact have worsened). Corn ethanol has displaced a portion of petroleum gasoline, but there is no evidence for the beginning of a broader transition to non-petroleum resources beyond the levels mandated by the RFS. If changes in energy use and GHG emissions of the magnitude given in this committee's task statement are to be achieved, the country will need a policy framework that is much more effective in moving the LDV-fuel system toward specified goals. Although a formal adaptive paradigm has not been used for transportation and energy policy to date, some guidance can be obtained from other contexts where it has been used. Insights can also be found in the history of public policies that have resulted in varying degrees of progress on the impacts of LDVs.

One issue for which discussions of adaptive policy have been published is that of climate adaptation, i.e., measures for handling the impacts of climate change rather than mitigating its causes. This body of work builds on prior thinking about adaptive frameworks for natural resource and ecological systems management. Swanson and Bhadwal (2009) characterize adaptive policies as those that not only anticipate the range of conditions that lie ahead, but also have an up-front design that is robust in the face of unanticipated situations. Aspects of such design include integrated and forward-looking analysis, policy development deliberations that involve multiple stakeholders, and the definition of key performance indicators that are then monitored in order to trigger automatic adjustments in parameters of the policy. Adaptive policies ideally are able to navigate toward successful outcomes even while encountering developments (including lack of hoped-for outcomes) that cannot be anticipated in advance.

An example of such an adaptive framework for the transport-sector GHG emissions is the proposal contained in a 2009 consensus report by the U. S. Climate Action Partnership (USCAP), a group of 31 corporations and public-interest groups. The USCAP proposal states (2009, p. 23):

> Congress should require EPA, in collaboration with the Department of Transportation (DOT) and other federal and state and local agencies, to carry out a periodic in-depth assessment of current and projected progress in transportation sector GHG emissions reductions. . . . This assessment should examine the contributions to emissions reductions attributable to improvements in vehicle efficiency and GHG performance of transportation fuels, increased efficiency in utilizing the transportation infrastructure, as well as changes in consumer demand and use of transportation systems, and any other GHG-related transportation policies enacted by Congress.
>
> On the basis of such assessments EPA, DOT and other agencies with authorities and responsibilities for elements of the transportation sector should be required to promulgate updated programs and rules—including revisions to any authorized market incentives, performance standards, and other policies and measures—as needed to ensure that the transportation sector is making a reasonably commensurate contribution to the achievement of national GHG emissions targets.

Committee members hold a range of views on the merits of the USCAP proposal. This committee presents its own proposal for an adaptive framework in Chapter 7.

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7

Policy Options

Previous chapters demonstrate that achieving a 50 percent reduction in petroleum consumption by light-duty vehicles (LDVs) by 2030 and 80 percent reductions in both petroleum consumption and greenhouse gas (GHG) emissions by LDVs by 2050 will be extremely challenging. What likely will be required to achieve those goals is some combination of the following:

- Major improvements in existing LDV powertrains;
- Major reductions in the weight and other loads of all sizes and types of LDVs;
- Changes in the energy resources or fuels used to power LDVs, and the effective control of net GHG emissions in the sectors that supply fuels for LDVs; and
- The successful introduction and widespread use of one or more entirely new powertrain systems (e.g., electric vehicles and fuel-cell electric vehicles [FCEVs]).

Reaching the ambitious goals for 2050 will be made easier by any reductions in the rate of growth in vehicle miles traveled (VMT) that might be practical and by technological advances that increase the operating efficiencies of transportation systems. However, the primary focus of the findings and policy options identified in this chapter is on how to bring about changes in vehicles and fuel supply sectors, and in consumer demand, necessary to meet the goals addressed in this study.

If the increases in new LDV fuel economy reflected in the standards finalized by the National Highway Traffic Safety Administration (NHTSA) and the U.S. Environmental Protection Agency (EPA) are attained by 2025, as noted in Chapter 5, considerable progress will have been made in moving the new LDV fleet toward lower levels of energy use and GHG emissions. This progress will have been achieved primarily by production and sale of LDVs with improved efficiency employing existing powertrain concepts, including conventional hybrid electric vehicles. Despite such progress, however, this strategy alone is insufficient to decrease LDV petroleum consumption by 50 percent by 2030.

To meet the goals addressed in this study, vehicle and fuel-supply advances will be needed in the period from 2025 through 2050. One possible pathway to meet the 2050 petroleum use and GHG emission reduction goals could be combining high LDV fuel economy with high levels of drop-in biofuels produced using processes with low net GHG emissions. Another possible pathway could be a transition to other alternative fuel and alternative powertrain technologies (e.g., plug-in hybrid electric vehicles [PHEVs], battery electric vehicles [BEVS], and FCEVs) to constitute a significant share of the on-road fleet by 2050. The time required for fleet turnover means that vehicles incorporating these technologies will need to begin to enter the new LDV fleet in significant numbers by the 2030s. The technical, economic, and consumer acceptance barriers currently faced by these technologies may have been largely overcome by then. The uncertainties about technology improvements and costs are such that the committee cannot rule out either pathway for meeting the goals addressed in this study.

If new fuels are required to enable use of alternative powertrain technologies, these fuels will have to be available widely enough by 2025 to enable early adopters not to be overly concerned about fuel availability. Because physical stock changes in major energy supply systems occur more slowly than LDV stock turnover, enough measurable progress in this regard must be seen by 2030 so that it is clear that the 2050 reductions of in-sector LDV GHG emissions enabled by the advanced powertrain technologies will not be largely offset by the emissions generated by the production and distribution of the fuels themselves.

The objective of the policy actions suggested in this chapter is to substantially increase the probability of achieving the goals specified in the statement of task. The policy options identified in this chapter as most promising by the committee are based on its review of the past experience with and potential effectiveness of the possible policies described in Chapter 6, and on the committee's own evaluation of policies and policy combinations in Chapter 5. Regulatory policies such as Corporate Average Fuel Economy (CAFE) standards, pricing policies (either economy-wide or directed at fuel supply sectors) such as feebates for vehicles, and regulatory or pricing policies directed at fuel supply sectors will likely be essential to attaining the 2050 goals for reducing LDV petroleum consumption and GHG emissions. Additional policies may also be required if a transition to alternative vehicle and fuel systems turns out to be the best way to attain the goals. Such transition policies include infrastructure investments and possible subsidies. Because of uncertainties and unforeseen circumstances in the future, policies must be adaptive in response to technology and to market conditions over time to ensure that the goals are met in a cost-effective way.

7.1 POLICIES TO ENCOURAGE THE CONTINUED IMPROVEMENT OF THE FUEL EFFICIENCY OF THE LIGHT-DUTY VEHICLE FLEET

Even if the fuel economy and CO_2 reduction standards for new LDVs currently being implemented by NHTSA and the EPA are met, further improvement in the fuel efficiency of vehicles could be made in and after model year (MY) 2025. Although the committee believes that it is premature to suggest a specific fuel economy target for new LDVs by MY2050, a "ballpark" estimate is that a further doubling (that is, a doubling beyond the doubling that is scheduled to occur between 2005 and 2025) of the average new LDV fleet fuel economy standard by 2050[1] will be technically feasible but costly. The modeling results in Chapter 5 indicate that such an increase in the CAFE standard could reduce GHG emissions by about 50 percent in 2050 compared to the 2005 level. Reaching such ambitious fuel economy targets will require a mix of policies that affect the decisions of vehicle manufacturers to produce fuel-efficient vehicles and the decisions of consumers to purchase them.

FINDING. The CAFE standard has been effective in reducing vehicle energy intensity, and further reductions can be realized through even higher standards if combined with policies to ensure that they can be achieved.

POLICY OPTION. The committee suggests that LDV fuel economy and GHG emissions standards continue to be strengthened to play a significant role after model year 2025 as part of this country's efforts to improve LDV fuel economy and reduce GHG emissions.

FINDING. "Feebates," rebates to purchasers of high-fuel-economy (i.e., miles per gallon [mpg]) vehicles balanced by a tax on low-mpg vehicles is a complementary policy that would assist manufacturers in selling the more-efficient vehicles produced to meet fuel economy standards.

POLICY OPTION. The committee recognizes that U.S. government "feebates" based on the fuel consumption of LDVs could have a role as a complement to LDV fuel economy and GHG emissions standards to facilitate and accelerate the introduction of significantly more efficient vehicles into the market to the meet the 2050 timing of the goals. The committee suggests that the U.S. government include "feebates" as part of a policy package to reduce LDV fuel use.

7.2 POLICIES TARGETING PETROLEUM USE

Petroleum consumption can be reduced by a variety of policies. Placing a quantity constraint on petroleum consumption (also known as rationing) would reduce its use directly and increase its price. A tax on petroleum would directly increase the price of petroleum, providing a signal to both producers and consumers to find ways to reduce use of petroleum-based fuels, redesign vehicles, or replace petroleum-based fuels with other fuels. Other approaches include requiring quantities of alternative fuels to be sold (such as through application of the Renewable Fuel Standard) or using subsidies to reduce the prices of alternative fuels to make their cost lower than the cost of petroleum-based fuels. As discussed in Chapter 6, it can be difficult to design a policy that successfully mandates the sale of certain fuels when they are more expensive than petroleum-based fuels. Subsidies require government revenue to fund, whereas taxes raise revenue that either can be used to fund programs related to energy and GHG emissions reduction or can be refunded to the taxpayer.

Placing a quantity limit on oil consumption (or use of petroleum fuels by LDVs specifically) has rarely been proposed and would be expected to have significant adverse social impacts.

What has been widely discussed for many years is taxation that would directly target petroleum demand or petroleum imports. Existing U.S. motor fuel taxes were adopted to raise revenues for funding roads. Historically, these taxes have helped support petroleum demand by facilitating vehicle use while remaining low enough to avoid significantly affecting fuel demand. A small exception to the historical rationale was the $0.043 per gallon gasoline tax increase of 1993 (the last time U.S. fuel taxes were raised), which had been proposed originally as a "Btu tax" to foster energy

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[1] Such a further doubling of on-road fleet fuel economy between 2025 and 2050 cannot, by itself, achieve the goals set forth in the charge to this committee. Additional changes involving fuels and VMT also will be needed. See the committee's scenarios in Chapter 4 for details.

conservation and reduce the federal deficit. However, the funds from that levy were redirected back to the Highway Trust Fund in 1997.

To be used extensively, alternative fuels, together with the vehicles that they power, would have to be at least price competitive with petroleum-based fuels and conventional vehicles. For compressed natural gas and hydrogen, the alternative fuels would have to be made available with complementary vehicle and refueling infrastructure. To undertake the large investments necessary for the development and widespread availability of any alternative fuels, the fuel producers and distributors will have to be convinced that there eventually will be a profitable market for those fuels, including assurance that they will not be undercut by low-cost petroleum. The price of petroleum-based fuels would have to be relatively high and stable for investors to be confident in the profitability of alternatives. One policy that has promise for creating price stability in the oil market is a tax on petroleum that moves inversely with petroleum price and is levied only when petroleum prices fall below a target level, as discussed in Chapter 6. This tax approach ensures the price stability necessary to provide better signals to investors to invest more in efficiency or in alternative energy sources.

FINDING. Taxes on petroleum-based fuels can create a price signal against petroleum demand, offset the "rebound effect" induced by increasingly efficient vehicles, and help assure innovators, producers, and distributors that there is a profitable market for improved efficiency in energy use and for alternative fuels. The range of possible tax policies includes a fixed tax rate per barrel on petroleum that is a surtax on current taxes, or a tax that moves inversely with the oil price when the price falls below a target level, thereby stabilizing prices so that they are at or above the target. Fuel subsidies or quantity mandates are more difficult than taxes to use effectively. Subsidies require government funding, and sometimes complex decisions about who is eligible for the subsidies. Until alternative fuels become cost competitive with petroleum-based fuels, quantity mandates for alternative fuels would require fuel producers to cross-subsidize their money-losing alternative fuels from their profitable petroleum-based fuels. Creating and then maintaining the conditions necessary for successful cross-subsidization would be difficult, politically and otherwise, for the government. Yet without adopting one or more of these policy approaches, the lure of eventual profitability necessary to induce investment is absent, and so the investment is unlikely to occur.

POLICY OPTION. High and stable oil prices would be helpful in transitioning away from oil use in LDVs and meeting the 80 percent reduction goal by 2050. If fluctuations in oil prices and often low oil prices persist, it may be necessary to impose a tax on domestic use of petroleum-based fuels or set a price floor target for petroleum-based fuels.

Taxing petroleum or implementing a price floor to prevent the decline of petroleum price beyond a certain level would discourage its use and contribute to reducing VMT and increasing the use of fuel-efficient internal combustion engine vehicles (ICEVs) if petroleum-based fuel remained the dominant fuel. (See Box 7.1 and see Section 6.3.5, "A Price Floor Target for Motor Fuels," in Chapter 6). A reduction in petroleum use also would reduce the social cost of oil consumption. (See Box 5.5, "Social Costs of Oil Dependence," in Chapter 5.)

FINDING. The Renewable Fuel Standard contributed to reducing petroleum use by LDVs. As a result of the failure of cellulosic biofuels to achieve commercial viability and the ability of the EPA to waive the requirement, the volume of cellulosic biofuels mandated by the RFS has repeatedly been reduced. The RFS could become more effective if the EPA's authority to reduce the mandated requirement either is eliminated so as to maintain a guaranteed market for any cellulosic biofuels produced or linked to a requirement to fund RD&D for progress toward the improved viability of cellulosic biofuels.

POLICY OPTION. The committee supports continuation of the Renewable Fuel Standard because it has been modestly effective in displacing petroleum. The committee suggests periodic review of the RFS by Congress to assess whether the mandated volumes should be increased and whether other alternative fuels should be included in the mandate to encourage the use of alternative fuels and reduce the share of petroleum-based fuels in use for LDVs. The committee also supports further research and analysis for refinement of the means of assessing how fuels qualify as renewable.

7.3 POLICIES TO REDUCE GHG EMISSIONS ASSOCIATED WITH LDV FUELS

Policies that reduce the overall energy demand of LDVs through improving vehicle efficiency and lowering travel demand contribute to a reduction in GHG emissions. In addition, reducing GHG emissions requires policies that limit the net GHG emissions associated with the fuels used by LDVs. In considering fuel-related policies, it is crucial to distinguish between the fuels themselves—that is, the end-use energy carriers used directly by vehicles—and the primary energy resources (such as fossil fuels) and associated energy sector systems that supply end-use fuels. GHG emissions from fuel use can be limited through three basic approaches:

BOX 7.1
The Case for Fuel Pricing

The case for fuel pricing policies is based on economic theory as well as experience: for most goods, raising the price reduces the quantity demanded. One way to reduce petroleum use or greenhouse gas (GHG) emissions is to tax them. GHG emissions are environmental externalities, and their full societal costs are not reflected in market prices. As discussed in Box 5.5 in Chapter 5, a range of estimates exist for the damage that may be caused by GHG emissions. The committee chose a value at the high end of the range, \$136.20 per metric ton of CO_2, because that is most consistent with the 80 percent GHG mitigation goal. There are excess social costs of oil dependence, as well, caused by the use of market power by oil producers, as well as increased public expenditures on defense (Greene and Leiby, 1993). As discussed in Box 5.6 in Chapter 5, a tax on the order of \$10.50 to \$38 per barrel with a midpoint of \$24 in 2009 dollars would be needed to reflect the full social costs of oil dependence.

Fuel prices affect producer and consumer behavior with respect to the three parameters that affect petroleum use and GHG emissions: fuels, vehicles, and vehicle miles traveled. Experience both here and abroad indicates that producers and consumers indeed respond to fuel prices (Sterner, 2007; Dahl, 2012) but that fuel demand is relatively inelastic. For example, estimates of the elasticity of demand for gasoline range from only 0.1 over short periods when it is difficult to modify use, to about 0.3 to 0.5 over longer periods when there are more opportunities to change behavior. One study finds that a tax on gasoline that increases to about \$2.00 a gallon by 2030 results in decreased gasoline use of about 25 percent over that same period (Krupnick et al., 2010). There is little experience with GHG pricing of transportation fuels and their supply chains, and so the overall GHG emissions response to including such pricing could be greater than the demand response alone.

There are also reasons why a fuel or GHG tax may need to be combined with other policies. Pricing gasoline to reflect its full costs will still not induce consumers to make optimal choices about fuel-efficient vehicles if they undervalue fuel economy (Greene, 2010). This point is discussed more fully in Chapter 5, but to the extent it is true, then a combination of pricing and vehicle standards will be important. The committee's scenario analyses suggest that significant ongoing fuel economy improvement is likely to play a very large role in meeting both the petroleum reduction and GHG emissions reduction goals (Greene, 2011; Allcott et al., 2012). That is why one of the committee's high-priority suggestions is to continue to strengthen vehicle standards for fuel economy and GHG emissions.

There are other reasons why pricing energy will be helpful in conjunction with such vehicle standards:

- Reducing VMT, including countering the rebound effect. Because fuel economy standards reduce the variable cost of driving, they encourage more driving, partially offsetting the fuel-use-reducing benefits of the standards. This phenomenon is called the rebound effect. Raising fuel prices counters the rebound effect and reduces the demand for fuel-consuming travel generally.
- Increasing demand for fuel-efficient vehicles. Higher fuel prices increase consumers' demand for fuel-efficient vehicles, thereby aligning the requirements faced by automakers under vehicle standards with the demands of consumers.

Any of these behavioral rationales for higher fuel taxation would represent a significant departure in U.S. fiscal policy. Traditionally, federal, state, and local fuel taxes have been justified only as a way to raise revenue for transportation infrastructure and maintenance. Federal U.S. gasoline taxes have not increased in nominal terms in almost 20 years; in real terms, they have declined dramatically, leading to crumbling roads, bridges, and tunnels. Other studies have documented a justification for higher fuel taxes in order to make up for this substantial shortfall in transportation funding (National Surface Transportation Policy and Revenue Study Commission, 2007). Thus, taxing fuels to reduce oil use and GHG emissions could have the important co-benefit of raising needed revenue for our transportation system. Although this behavioral rationale for fuel pricing is not traditional in U.S. policy, it has been used in Western Europe and other countries and is one reason for the higher levels of vehicle fuel economy and lower levels of per capita demand for automobile travel observed in those countries relative to the United States.

- By counterbalancing the end-use (vehicular) CO_2 emissions from carbon-based fuels with sufficient net CO_2 uptake elsewhere. Because this CO_2 uptake and the emissions associated with feedstock growth and processing (e.g., for biofuels) occur outside the transportation sector, the optimal policies are not those directed at the transportation sector per se, but rather measures to address net GHG emissions in fossil fuel extraction and refining, biorefining, agriculture, forestry, and related land-use management sectors involved in supplying carbon-based fuels. (See also Chapter 6.) In the future, counterbalancing also might occur through geologic storage or biological sequestration techniques.
- By using physically carbon-free fuels such as electricity or hydrogen, which avoid release of CO_2 from vehicles themselves. These energy carriers must then be supplied from low-GHG emitting-production sectors. Therefore, optimal policies are not those directed at the transportation sector per se, but rather measures addressing electric power generation and other industrial sectors that produce carbon-free fuel.

- By capturing and preventing the release of the CO_2 produced during combustion or other utilization of carbon-based fuels directly on vehicles, or by avoiding the production of CO_2 during on-board energy utilization. Because no practical means of on-board CO_2 capture or avoidance are currently known, this third approach is not considered in this report.

This list demonstrates that it is impossible to have a complete policy for controlling auto-sector GHG emissions in isolation from policy to control emissions in other sectors, namely, those that supply energy and feedstock for fuel production. This principle is true whether the fuel is carbon-based or carbon-free. The extent to which policies are also needed to affect the choice of vehicular fuel depends on whether a change of end-use energy carrier is required. That question cannot be resolved on the basis of present scientific knowledge. As the committee's scenario analyses demonstrate, some technological approaches for meeting the task statement goals entail entirely new fuels and fuel distribution systems, but others (namely, the use of drop-in biofuels in high-efficiency vehicles) do not. In each scenario evaluated where the goals are achieved, a major change is required in the energy sectors that supply automotive fuel.

The committee recognizes that GHG emissions that occur in the non-transportation sectors involved in supplying energy and feedstock for fuel production need to be addressed to reduce net GHG emissions effects of the LDV sector. However, a thorough treatment of policies for addressing GHG emissions that occur in the non-transportation sectors is beyond the scope of this study. (See Appendix A for the statement of task.) Either an economy-wide GHG policy or a coordinated multisector GHG policy is likely to offer the most economically efficient and equitable way to achieve deep GHG emissions reductions across multiple sectors. Broadly speaking, the options for multisector GHG policy include direct regulation of GHG emissions under the Clean Air Act (CAA), carbon taxation, or a cap-and-trade system that blends elements of regulatory and fiscal policies by placing an economy-wide limit on GHG emissions and propagating a price signal to motivate emissions reductions across multiple sectors.

The EPA is beginning to pursue CAA regulation of GHG emissions; however, without new congressional authorization, the agency might not pursue targets that are stringent enough to support GHG emissions reduction of 80 percent by 2050. Carbon taxation is another way to motivate reductions. If the policy is of stringency comparable to that of setting a cap on energy supply sector GHG emissions at about 20 percent of the 2005 level by 2050, it would encourage GHG emissions reduction from other sectors (e.g., electricity and agriculture) that would contribute to reducing GHG emissions from the LDV sector. However, determining the tax level needed will be difficult. Given the large revenues that would result (which could be helpful for federal finances), pursuing a carbon tax would entail engaging in a major fiscal policy discussion that affects many other aspects of national policy.

Although the near-term political prospects of cap-and-trade are poor, it may ultimately be favored over other options. It was the leading national GHG policy option in prior Congresses. Cap-and-trade once had some bipartisan support even though it fell short of sufficient majority support. California is implementing an economy-wide GHG cap-and-trade through its AB 32 program. The northeast Regional Greenhouse Gas Initiative is implementing a GHG cap-and-trade program for the power sector.

FINDING. Meeting the GHG emissions reduction target of this study requires addressing the upstream emissions that occur in the non-transportation sectors involved in supplying energy and feedstock for fuel production. Substituting hydrogen, biofuels, or electricity for petroleum-based gasoline in vehicles will result in net GHG emissions reductions only if these alternative fuels are produced using technologies and processes that emit few GHGs. Carbon capture and storage (CCS) is likely a critical technology for producing low-GHG hydrogen and electricity, but other options that directly produce electricity and can indirectly produce hydrogen through electrolysis exist (e.g., nuclear and renewable power).

POLICY OPTION. A policy that addresses GHG emissions from the energy sources and sectors that supply fuels used in LDVs is needed if GHG emissions from the LDV sector, including upstream emissions, are to be reduced enough to meet the 2050 goals. That policy can take the form of a set of measures that are specific to each sector that affects fuel production and distribution, or it can embody a comprehensive approach to addressing GHG emissions (e.g., a carbon tax or a carbon cap-and-trade policy).

7.4 POLICIES TO REDUCE THE RATE OF GROWTH OF VMT

As shown in the previous chapter, increases in vehicle miles traveled by LDVs have offset much of the potential reduction in petroleum use and in GHG emissions caused by improved fuel economy over the last several decades. If VMT increases at the rates projected in the "business as usual" scenario described in Chapter 5, the same is likely to be true in the decades ahead.[2]

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[2] The "business as usual" and "reference" cases assume a slowdown in the rate of growth of VMT in the future. Nevertheless, in these cases, as well as in the committee's simulations, VMT continues to grow. This growth in VMT will offset some of the reductions in petroleum use and GHG emissions that otherwise would occur.

A range of policy options exists that have the potential to reduce VMT growth, but they differ widely in their likely impact. For example, policies to increase residential density are likely to produce limited results on a national scale. As discussed in Chapter 6, a previous National Research Council (NRC) report has found that a doubling in density of 75 percent of the new development by 2050, something that the report characterizes as "require[ing] such a significant departure from current housing trends, land use policies of jurisdictions on the urban fringe, and public preferences that they would be unrealistic absent a strong state or regional role in growth management," would reduce VMT by only 8 to 11 percent below what it otherwise would be in 2050 (NRC, 2009). And even this extremely optimistic degree of doubling of the density of new residential development would have to be accompanied by large increases in the amount of mixed-use development and in the quality and accessibility of transit. A major study of the potential impact of other much-discussed factors, such as pedestrian and bicycle strategies, has shown them to have only a small impact on national VMT (NRC, 2009).

Indeed, the policies found to have the most significant impact on VMT are those that raise the marginal cost of driving—for example, increasing fuel taxes. Other possible policies would be "pay at the pump" insurance, a means by which vehicle owners can pay for their car insurance through charges added to the price of gasoline, or a road-user charge. A road-user charge of $0.12 per mile would have an effect on the variable cost of driving roughly comparable in magnitude to the effect of current West European motor fuel taxes. The report *Moving Cooler. An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions* estimated that a charge of this level would reduce 2050 VMT by 5 percent, and that just the VMT impact portion of a carbon tax levied at similar levels would reduce 2050 VMT by almost 8 percent (Collaborative Strategies Group, 2009).

FINDING. The policies that have the most significant impact on reducing the rate of growth of VMT are those that raise the marginal cost of driving. Policies other than those that raise the marginal cost of driving could result in significant reductions in the rate of VMT growth or even reductions in total VMT in certain individual urban areas, but they are not likely to result in significant reductions in GHG emissions or petroleum use at the national level by 2050.

POLICY OPTION. If reducing VMT growth is to be pursued to meet the study goals of reducing petroleum use and GHG emissions, policies that increase the marginal cost of driving should be considered.

7.5 POLICIES TO ENCOURAGE RESEARCH AND DEVELOPMENT, DEMONSTRATION, AND DEPLOYMENT

As discussed in Chapter 6, the federal government has implemented a range of policies intended to encourage the development and use of fuel-efficient LDVs and the alternative fuels to power them, with mixed success. Stages of advancement for new technologies are separated into research and development (R&D) (which involves basic and applied research on improvements to or evolution of the technology, including prototypes), demonstrations (which test the feasibility of developed technology, including significant impediments to commercial success), and deployment of the technology into the market at large scale.

The government's role in facilitating each of these stages varies with the type of technology, how far along in the advancement process the technology for either the vehicle or the fuel has progressed, and what policies are already in place. For example, new technologies for advanced ICEVs and hybrid vehicles powered by gasoline are continually developed, and regulatory policies such as CAFE and pricing policies such as feebates encourage the market adoption of fuel-efficient technologies and vehicle designs. Other powertrains and fuels, such as FCEVs, BEVs, hydrogen fuels produced with low net GHG emissions, and biofuels are at early stages of commercialization. BEVs have been introduced commercially, although sales are still low. Several companies have demonstrated FCEVs at small scale and expect to start introducing them commercially by 2015. However, significant technology and production progress is needed for cost reduction before these vehicles will be competitive at scale with existing ICEVs. Some alternatives to petroleum are at early stages of development, and demonstrations may be important in addition to R&D.

7.5.1 Research and Development

There is a strong case for R&D, whether public or private, to advance the intellectual infrastructure of the country for meeting technical challenges, as discussed in Chapter 6.

FINDING. Fuel cells, batteries, biofuels, low-GHG production of hydrogen, carbon capture and storage, and vehicle efficiency should all be part of the current R&D strategy. It is unclear which options may emerge as the more promising and cost-effective. At the present time, foreclosing any of the options the committee has analyzed would decrease the chances of achieving the 2050 goals. The committee believes that hydrogen fuel cell vehicles are at least as promising as battery electric vehicles in the long term and should be funded accordingly. Both pathways show promise and should continue to receive federal R&D support.

POLICY OPTION. The committee supports consistent R&D to advance technology development and to reduce the costs of alternative fuels and vehicles. The best approach is to promote a portfolio of vehicle and fuel R&D, supported by both government and industry, designed to solve the critical technical challenges in each major candidate pathway. Such primary research efforts need continuing evaluation of progress against performance goals to determine which technologies, fuels, designs, and production methods are emerging as the most promising and cost-effective.

FINDING. Current methods for the accounting of net GHG emissions associated with the production and use of transportation fuels involve numerous uncertainties. Reducing the uncertainties and developing robust accounting approaches are important for defining R&D strategies, guiding private sector investments, and developing effective public policies for reducing the net GHG emissions associated with fuels used by light duty vehicles.

POLICY OPTION. Because of the uncertainties associated with existing methods of accounting for the net GHG emissions impacts of the production and use of transportation fuels, especially for electricity, biofuels, and hydrogen, the committee suggests further efforts to develop accounting methods to account for GHG emissions that are applicable to the design of public policies for addressing these impacts.

7.5.2 Demonstration

The alternative vehicles discussed in Chapter 2 have demonstrated their performance readiness. Remaining challenges are cost reduction and further advancement through continued R&D, and potentially, successful deployment. Private industry may choose to demonstrate new technologies or new vehicle models or prototypes, but the need for further government involvement appears to be limited to areas of special government interest, such as validating the safety or performance of alternative vehicles.

For fuels, vehicles, and GHG management technologies that show promise of commercial readiness, appropriately scaled demonstration projects that are supported by both industry and government are likely to be important for validating feasibility, proving physical and environmental safety, and establishing cost-effectiveness. The results of such demonstrations could provide essential information for identification of which alternative fuel and GHG management technologies have long-term potential to both compete with gasoline in the marketplace and achieve GHG emissions reduction goals, and to establish readiness for deployment. Another appropriate role for the government is the coordination of integrated demonstrations of promising vehicles and fuel systems or stations.

FINDING. Demonstrations are needed for technologies to reduce GHG emissions at appropriate scale (e.g., hydrogen produced with low net GHG emissions and CCS) to validate performance, readiness, and safety.

FINDING. Integrated demonstrations of vehicles and fueling infrastructure are necessary to promote understanding of performance, safety, consumer use, and other important characteristics under real-world driving conditions.

POLICY OPTION. The committee supports the government's involvement in limited demonstration projects at appropriate scale to promote understanding of the performance and safety of alternative vehicles and fueling systems. For such projects, substantial private sector investment should complement the government investment, and the government should ensure that the demonstration incorporates well-designed data collection and learning to inform future policy making and investment. The information collected with government funds should be made available to the public consistent with applicable rules that protect confidential data.

7.5.3 Deployment

Many of the findings and policy options mentioned earlier in this chapter will encourage deployment of highly efficient or alternative vehicles and alternative fuels, and policy will be a critical driver of deployment. Policy options include CAFE and feebate policies for vehicles, performance standards, consumption mandates or pricing policies for fuels, and carbon control policies. Modeling results described in Chapter 5 show that such policies will greatly increase the shares of highly efficient and alternative vehicles over time. However, Chapter 5 also found that additional deployment policies will likely be needed for some alternative-vehicle fuel systems if they are to be part of the strategy to attain the significant reductions in petroleum use and GHG emissions discussed in this report. Additional policies such as subsidies or mandates for vehicles or fuel infrastructure investment will depend on the path of future technology, market conditions, and the urgency of the energy security and climate-change issues that these fuels are needed to address. The timing of additional deployment policies is critical and will depend on how close any one technology or combinations of technologies are to market readiness. At present, it is unclear which vehicle and fuel technology or technologies will have consumer acceptance and the best potential for lowest costs at scale to achieve the goals addressed in this study. Data on the costs of particular technologies will accumulate over time and will inform future policy decisions.

In addition, for alternative-vehicle fuel systems, the government, in partnership with industry, will likely have a role in coordinating the commercial deployment of alternative vehicles with the fueling infrastructure for those vehicles. Coordination of vehicle sales and provision of refueling infrastructure are more challenging for hydrogen than for electricity or natural gas because hydrogen requires a completely new, large-scale fuel production and delivery system. In contrast, natural gas and electricity already have a large, robust, and ubiquitous distribution system, and the additional deployment needed is an accessible dispensing infrastructure.

Assessments of the readiness of affected technologies and continuous assessments of the effectiveness of deployment policies are important. Such assessments would require metrics to be established to determine when to initiate a deployment effort, to assess progress during initial deployment, to guide adjustments based on the achieved results, and to determine when to terminate deployment efforts that are ineffective or have been overcome by events. Starting deployment prematurely will increase the chance of failure and costs, extend the time for support, and undermine public confidence. Yet prolonged delay in deployment risks failure to meet the GHG emissions reduction and fuel saving goals. Determining technical and market readiness is challenging and should involve an unbiased expert review of available data, and consideration of the viewpoints of applicable stakeholders. In particular, the analysis in Chapter 5 indicates that subsidies of particular vehicles and fuels as a deployment strategy may be important, but careful and periodic evaluations are needed to ensure their effectiveness.

FINDING. The commercialization of fuel and vehicle technologies is best left to the private sector in response to performance-based policies, or policies that target reductions in GHG emissions or petroleum use rather than specifc technologies. Performance-based policies for deployment (e.g., CAFE standards) or technology mandates (e.g., RFS) do not require direct government expenditure for particular vehicle or fuel technologies. Additional deployment policies such as vehicle or fuel subsidies, or quantity mandates directed at specific technologies are risky but may be necessary to attain large reductions in petroleum use and GHG emissions.

POLICY OPTION. The committee suggests that an expert review process independent of the agencies implementing the deployment policies and also independent of any political or economic interest groups advocating for the technologies being evaluated be used to assess available data, and predictions of costs and performance. Such assessments could determine the readiness of technologies to benefit from policy support to help bring them into the market at a volume sufficient to promote economies of scale. If such policies are implemented, they should have specific goals and time horizons for deployment. The review process should include assessments of net reductions in petroleum use and GHG emissions, vehicle and fuel costs, potential penetration rates, and consumer responses.

FINDING. For alternative-vehicle fuel systems, government involvement with industry may be needed to help coordinate commercial deployment of alternative vehicles with the fueling infrastructure for those vehicles.

The committee's analysis found that the timing and the scope of policy-related actions have a major influence on the successful transition to new vehicle and fuel technologies. If the policies are insufficient, ill-targeted, or improperly timed to overcome the cost barriers to making the transition, then the transition will not occur and the costs of the policy-related actions can be wasted.

7.6 THE NEED FOR AN ADAPTIVE POLICY FRAMEWORK

FINDING. Many uncertainties surround not only advanced vehicle, fuel, and energy supply technologies but also the response of the many LDV market actors to policies implemented for meeting goals such as those described in this committee's task statement. Therefore, policy makers will be well served to establish an adaptive framework that enables the set of measures enacted to be systematically adjusted as the world changes and as new information becomes available while staying on track to meet the long-term policy goals.

As found in Chapter 6, such a framework should not only anticipate the range of conditions that lie ahead but also be designed to be robust in the face of unanticipated developments. Aspects of such policy design include provisions for integrated and forward-looking analysis, policy development deliberations involving multiple key stakeholders, and performance metrics that are monitored to trigger automatic adjustments in parameters of the policy. To be effective, such a framework requires the establishment of clear, measurable, and durable goals. Because of the uncertainty about which technologies would emerge as most effective and cost-effective, and about how consumers will respond to those technologies and fuel delivery systems, new evidence and information will be key to developing the best policies. Chapter 5 (see Section 5.7, "Simulating Uncertainty About the Market's Response") illustrates the dilemma in setting policy in the absence of good information about key aspects of consumer preferences on the demand side, and learning and scale economies on the supply side of the market. This and other information would have to be provided by various sources, and its assessment will inform effective policy decisions.

FINDING. The policies and measures needed to achieve the petroleum and GHG emissions reduction goals stated in the committee's statement of task will be implemented by more than one federal agency, as well as coordinated with state and local jurisdictions. Moreover, as experience is gained and new information becomes available, adjustments will be needed and will be coordinated across the implementing agencies.

POLICY OPTION. To meet the petroleum-use and GHG reduction goals stated in the statement of task, the committee considers it desirable to define a federal light-duty vehicle petroleum and GHG emissions reduction policy with the following elements:

- **Establish overall goals (e.g., via congressional action).**
- **Assign relevant federal agencies having jurisdiction over LDV energy use and GHG emissions, in collaboration with the other relevant federal, state, and local agencies, to carry out periodic assessments of progress against the goals and to report the results. The assessments would include:**
  - **— Quantifying progress to date and assessing the efficacy of the programs and policies in use for reducing petroleum use and GHG emissions;**
  - **— Identifying the causes of emerging shortfalls in meeting the goals, and the steps being taken and planned to remedy those shortfalls, consistent with the authority of the implementing agencies; and**
  - **— Identifying changes in implementing authority needed to remedy shortfalls and recommending those changes to Congress.**

If national policies are established to address these issues more broadly across the economy, then this LDV sector adaptive policy should be coordinated with, and appropriately incorporated within, the overall national energy and climate policy framework.

7.7 THE NEED FOR PUBLIC INFORMATION AND EDUCATION

FINDING. The committee considers that a vigorous program of public information and education is essential to the success of the other recommended policies and thus to achievement of the twin goals of reduced GHG emissions and reduced use of petroleum-based fuels. Increased research regarding public understanding and attitudes associated with these issues would inform the design of improved public information and education programs. Because the payoff of public education and information programs is long term and is typically measured in public benefit rather than direct financial return, it is critical that government be involved in developing and fostering such programs, because they tend to be underprovided by the private sector.

POLICY OPTION. If the United States is to achieve the goals of reduced petroleum use and reduced GHG emissions from the LDV fleet, then U.S. policy makers could develop public programs aimed at informing consumers of the goals to be achieved, the reasons such achievement is necessary, and the nature of the costs and benefits—individual and societal—to be derived from the policies being implemented.

As noted elsewhere in this report, the committee has differing views regarding the value of public promotion of specific alternative vehicle and fuel technologies, a difference of view that carries over into public information policy. Where there is agreement is in the value of informing consumers about the broad importance of the national goals, the connection with fuel economy and perhaps other objective vehicle environmental performance metrics to these goals, and the value of choosing highly fuel-efficient vehicles accordingly.

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Appendixes

A

Statement of Task

The NRC will appoint an ad hoc study committee to conduct a comprehensive analysis of energy use within the light-duty vehicle transportation sector, and use the analyses to conduct an integrated study of the technology and fuel options (including electricity) that could reduce petroleum consumption and greenhouse gas emissions. As was accomplished with the NRC *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen* study, the study will address the following issues over the time frame out to 2050:

- Assess the current status of light-duty vehicle technologies and their potential for future improvements in terms of fuel economy and costs including:
  —Advanced conventional ICE and hybrid-electric vehicles, including improved combustion and rolling resistance, and weight reduction (safety implications of lighter weight vehicles will be considered);
  —All-electric and plug-in hybrid electric vehicles;
  —Hydrogen fueled ICE and fuel cell vehicles;
  —Biofueled vehicles; and
  —Natural gas vehicles.
- Assess the status and prospects for current and future fuels and electric power that would be needed to power the vehicles. A variety of alternative fuels will be considered such as hydrogen, fuels derived from fossil feedstocks, and different biofuels derived from biomass feedstocks.
- Develop scenarios or estimates of the rate at which each of the vehicle technologies considered might be able to penetrate the market and what would be the associated costs, greenhouse gas emissions and petroleum consumption impacts out to 2050. This would also include the infrastructure needs either for production of the vehicles or supplying the energy requirements for the vehicles. Costs would be put on a consistent basis to serve as a better index of comparing options. Scenarios will consider technology as well as policy options and consider the likelihood of achieving 50 percent reduction in petroleum consumption by 2030 as well as 80 percent reduction in petroleum consumption and greenhouse gas emissions by 2050. In addition to technology, potential reduction in vehicle miles traveled (VMT) will also be considered.
- Identify the barriers that might exist in transitioning to these vehicle and fuel technologies.
- Consider and compare, as appropriate, the results to those obtained in recent National Academies studies as well as in other outside analyses and make comparisons based on similar assumptions and cost and benefit calculations.
- Recommend improvements in, and priorities for, the federal R&D program activities to accelerate the development of the most promising technologies.
- Suggest policies and strategies for achieving up to 80 percent reduction in petroleum consumption and carbon dioxide emissions by 2050 through commercial deployment of the light-duty vehicle technologies analyzed in the study.
- Write a report documenting the analyses, conclusions, and recommendations.

To the extent possible the committee will consider issues relating to vehicle duty cycles, regional distinctions, and technology development timelines and will build on the recent work of the National Academies reports as well as other recent studies that have been conducted.

B

Committee Biographies

DOUGLAS M. CHAPIN (NAE), *Chair*, is a principal of MPR Associates, Inc., Alexandria, Virginia. He has extensive experience in electrical, chemical, and nuclear engineering, with particular application to nuclear and conventional power plant problems and functions, including numerous aspects of power plant systems and associated components. He has worked in such areas as instrumentation and control systems, nuclear fuels, fluid mechanics, heat transfer, pumps, advanced analysis methods, test facility design, and electrical systems and components. Dr. Chapin has worked on a number of efforts including the Japan/Germany/United States research program on loss of coolant accidents, served as project leader for the design, construction, and testing of the loss of fluid test facility, was a member of the Electric Power Research Institute's (EPRI's) Utility Review Committee on Advanced Reactor Designs, and worked with the Utility/EPRI Advanced Light Water Reactor Program that defines utility requirements for future nuclear power plants. He was chair of the NRC's Committee on Application of Digital Instrumentation and Control Technology to Nuclear Power Plant Operations and Safety. He has served on a number of NRC committees, including the Committee on America's Energy Future, the Committee on Review of Department of Energy's (DOE's) Nuclear Energy R&D Program, and Board on Energy and Environmental Systems (chair). Dr. Chapin is a member of the National Academy of Engineering (NAE). He served as a member of the NAE's Electric Power/Energy Systems Engineering Peer Committee and as a member of the NAE's Committee on Membership. He is also a fellow of the American Nuclear Society. He has a B.S. degree in electrical engineering, Duke University, an M.S. degree in applied science, George Washington University, and a Ph.D. degree, nuclear studies in chemical engineering, Princeton University.

RALPH J. BRODD is president of Broddarp of Nevada, Inc., a consulting firm specializing in technology assessment, strategic planning and battery technology, production, and marketing. Dr. Brodd began his career at the National Bureau of Standards studying electrode reactions and phenomena that occur in battery operation. In 1961, Dr. Brodd joined the L.T.V. research Center of Ling Temco Vought, Inc., where he established a group in fuel cells and batteries. In 1963, he moved to the Battery Products Technology Center of Union Carbide Corporation, with technical management responsibilities for nickel-cadmium and lead acid rechargeable batteries, alkaline and carbon-zinc product lines, and exploratory R&D. He joined ESB (INCO Electroenergy, Inc.) in 1978 as director of technology. In 1982, Dr. Brodd established Broddarp, Inc., a consulting firm specializing in battery technology, strategic planning, and technology planning. He moved to Amoco Research Center as project manager of a rechargeable lithium sulfur dioxide battery project. He subsequently moved to Gould, Inc., to establish their Lithium Powerdex Battery Venture and then to Valence Technology, a venture group developing a solid polymer electrolyte battery system for rechargeable batteries for portable consumer devices as vice president, marketing. Dr. Brodd was elected president of the Electrochemical Society in 1981 and honorary member in 1987. He was elected national secretary of the International Society of Electrochemistry (1977-1982) and vice president (1981-1983). He is past chairman of the Board of Directors of the International Battery Materials Association (IBA). Dr. Brodd has more than 100 publications and patents. He received a B.A. degree in chemistry from Augustana College and M.A. and Ph.D. degrees in physical chemistry from the University of Texas at Austin.

GARY L. COWGER (NAE) is currently chairman and CEO of GLC Ventures, LLC—a management consultancy. He retired from General Motors Corporation as Group Vice President—Global Manufacturing, Labor Relations and Manufacturing Engineering. In this position he was responsible for all of GM's Global Manufacturing Operations. He held a variety of other senior positions at GM, including President of GM North America; Chairman—Adam Opel, AG; Vice President for Operations, GM Europe; and President and Managing Director of GM de Mexico. Mr. Cowger has extensive experience in business, technology, engineering and manufacturing operations. He was responsible for the development and implementation of the GM global manufacturing system. He has also had extensive experience in benchmarking, target-setting, and the creation and application of organizational and production-based performance measures. Mr. Cowger is the past Chairman of the Board for Kettering University and holds other Board positions in private and public organizations. Mr. Cowger holds an M.S. degree in management from the Massachusetts Institute of Technology and a B.S. degree in industrial engineering from Kettering University (formally General Motors Institute).

JOHN M. DeCICCO is a professor of practice at the School of Natural Resources and Environment and research professor at the University of Michigan Energy Institute. Previous positions include senior fellow, automotive strategies, Environmental Defense Fund; transportation program director, American Council for an Energy-Efficient Economy; and staff scientist, National Audubon Society. His teaching and advising interests address energy use and greenhouse gas (GHG) emissions from transportation as well as broader aspects of sustainable mobility and energy use. His research seeks to further public understanding of transportation systems and GHGs, including the interlinked decision-making structures (both private market and public process) that underpin energy demand and emissions in the sector. He has published widely on analysis of the cost and improvements in emissions and fuel economy of advanced automotive technologies and in recent years has focused increasingly on the challenges of transportation fuels and GHG emissions. He has a Ph.D. in mechanical engineering from Princeton University, an M.S.M.E. from North Carolina State University, and a B.A. in mathematics from Catholic University of America.

GEORGE C. EADS retired from Charles River Associates in 2008 after serving 12 years as a vice president. He remains a senior consultant with the company. Prior to joining CRA, Dr Eads held several positions at the General Motors Corporation, including vice president and chief economist; vice president, Worldwide Economic and Market Analysis Staff; and vice president, Product Planning and Economics Staff. Before joining GM, Dr. Eads was dean of the School of Public Affairs at the University of Maryland, College Park, where he also was a professor. Before that, he served as a member of President Carter's Council of Economic Advisors, was a program manager at the RAND Corporation, served as executive director of the National Commission on Supplies and Shortages, as Assistant Director of President Ford's Council on Wage and Price Stability, and taught at Harvard University, Princeton University, and the George Washington University. He has been involved in numerous projects concerning transport and energy. In 1994 and 1995, he was a member of President Clinton's policy dialogue on reducing greenhouse gas emissions from personal motor vehicles. He co-authored the World Energy Council's 1998 report *Global Transport and Energy Development—The Scope for Change*. He was Lead Consultant to the World Business Council for Sustainable Development's Sustainable Mobility Project, a project funded and carried out by 12 leading international automotive and energy companies. Dr. Eads is a member of the Presidents' Circle of the National Academies. He is an at-large director of the National Bureau of Economic Research. He received a Ph.D. degree in economics from Yale University. He has been on several National Academies committees, including the TRB study on Potential Energy Savings and Greenhouse Gas Reductions from Transportation, the TRB study on Climate Change and U.S. Transportation, and the America's Climate Choices study.

RAMON L. ESPINO is currently a research professor at the University of Virginia, where he has been on the faculty since 1999. Prior to joining the Department of Chemical Engineering, he was with ExxonMobil for 26 years. He held a number of research management positions in petroleum exploration and production, petroleum process and products, alternative fuels and petrochemicals. He has published about 20 technical articles and holds 9 patents. Dr. Espino's research interests focus on fuel cell technology, specifically in the development of processors that convert clean fuels into hydrogen and of fuel cell anodes that are resistant to carbon monoxide poisoning. Another area of interest is the conversion of methane to clean liquid fuels and specifically the development of catalysts for the selective partial oxidation of methane to synthesis gas. He has served on NRC committees dealing with R&D in DOE's fossil fuels programs, mitigation of greenhouse gases and other topics related to energy efficiency. He received a B.S. degree in chemical engineering from Louisiana State University and an M.S. and a doctor of science in chemical engineering from MIT.

JOHN GERMAN is a senior fellow for the International Council for Clean Transportation, with primarily responsibility for technology innovation and U.S. policy development. He has been involved with advanced technology and efficiency since joining Chrysler in 1976, where he spent eight years in Powertrain Engineering working on fuel economy issues. He then spent 13 years doing research and writing regulations for EPA's Office of Mobile Sources' laboratory in Ann Arbor, Michigan. Prior to joining ICCT four years ago, he spent 11 years as Manager of Environmental and Energy Analyses for American Honda Motor Company, with an emphasis on being a liaison between Honda's R&D people in Japan and regulatory affairs. Mr. German is the author of a book on hybrid gasoline-electric vehicles published by SAE and a variety of technical papers, including the future of hybrid vehicles, technology costs and benefits, consumer valuation of fuel savings, feebates, and light truck trends. He was the first recipient of the Barry D. McNutt award, presented annually by SAE for Excellence in Automotive Policy Analysis. He has a bachelor's degree in physics from the University of Michigan and partial credit toward an MBA.

DAVID L. GREENE is a corporate fellow of Oak Ridge National Laboratory, where he has researched transportation energy policy issues for the U.S. government for 35 years, a Senior Fellow of the Howard H. Baker, Jr. Center for Public Policy and a Research Professor of Economics at the University of Tennessee. Greene is an author of more than 250 publications on transportation, energy and related issues. He is an emeritus member of both the Energy and Alternative Fuels Committees of the Transportation Research Board and a lifetime National Associate of the National Academies. He is a recipient of the TRB's 2012 Roy W. Crum Award for distinguished achievement in transportation research, the TRB's Pyke Johnson Award, the Society of Automotive Engineers' 2004 Barry D. McNutt Award for Excellence in Automotive Policy Analysis, the Department of Energy's 2007 Hydrogen R&D Award and 2011 Vehicle Technologies R&D Award, the International Association for Energy Economics' Award for Outstanding Paper of 1999 for his research on the rebound effect, the Association of American Geographers' 2011 Edward L. Ullman Award, and was recognized by the Intergovernmental Panel on Climate Change for contributions to the IPCC's receipt of the 2007 Nobel Peace Prize. He holds a B.A. from Columbia University, an M.A. from the University of Oregon, and a Ph.D. in geography and environmental engineering from the Johns Hopkins University.

JUDI GREENWALD is the vice president of technology and innovation at the Center for Climate and Energy Solutions. She oversees the analysis and promotion of innovation in the major sectors that contribute to climate change, including transportation, electric power, and buildings. Ms. Greenwald focuses on technology, business, state, regional, and federal innovation. She served on the Resource Panel for the northeast Greenhouse Gas Initiative and the California Market Advisory Committee, and as a policy advisor to the Western Climate Initiative and the Midwest Greenhouse Gas Accord Advisory Group. She previously served as the vice president for innovative solutions at the Pew Center on Global Climate Change, C2ES's predecessor organization. Ms. Greenwald has nearly 30 years of experience working on energy and environmental policy. Prior to coming to the Pew Center, she worked as a consultant, focusing on innovative approaches to solving environmental problems, including climate change. She also served as a senior advisor on the White House Climate Change Task Force. As a member of the professional staff of the Energy and Commerce Committee of the U.S. House of Representatives, she worked on the 1990 Clean Air Act Amendments, the 1992 Energy Policy Act, and a number of other energy and environmental statutes. She was also a congressional fellow with then-Senate Majority Leader Robert C. Byrd, an environmental scientist with the U.S. Nuclear Regulatory Commission, and an environmental engineer and policy analyst at the EPA. Ms. Greenwald has a B.S. in engineering, cum laude, from Princeton University and an M.A. in science, technology and public policy from George Washington University.

L. LOUIS HEGEDUS (NAE) is the retired senior vice president, R&D, of Arkema Inc., and a visiting distinguished fellow at RTI International. Research programs at Arkema supported market applications in the automotive, petroleum, energy conversion and storage, electronics, and construction industries. Dr. Hegedus was previously vice president, Corporate Technical Group, at W.R. Grace. Research programs included catalysts for petroleum refining, chemicals, emission control, and fuel cells; technical and electronic ceramics; electrochemical products including polymeric membranes for electric storage batteries of various types; and construction materials and products. Prior to joining W.R. Grace, Dr. Hegedus was affiliated with the General Motors Research Laboratories where he managed research on the development of the catalytic converter for automobile emission control. Before his graduate studies, he was an engineer with Daimler-Benz in Germany. He is a member of NAE, and he is a recipient of the R.H. Wilhelm, Professional Progress, Catalysis and Reaction Engineering Practice, and the Management Division awards of the American Institute of Chemical Engineers (AIChE) and the Leo Friend Award of the American Chemical Society (ACS)-Chemtech. At the occasion of their 100th anniversary, AIChE named Dr. Hegedus as one of "Hundred Chemical Engineers of the Modern Era." He was a founding member of AIChE's Commission on Energy Challenges and has served on several panels of the NRC's Board on Chemical Sciences and Technology, including one on critical chemical technologies, one on the future of catalysis, and one charged with the international benchmarking of the U.S. chemical engineering competencies. Most recently, Dr. Hegedus served on panels of the National Science Foundation dealing with the manufacture of nanomaterials and with the development of rechargeable lithium battery technology. At RTI International, he co-edited and co-authored the book *Viewing America's Energy Future in Three Dimensions—Technology, Economics, Society*. Dr. Hegedus obtained his Ph.D. in chemical engineering from the University of California, Berkeley, and his M.S. in chemical engineering from the Technical University of Budapest, from which he also received an honorary doctorate.

JOHN B. HEYWOOD (NAE) has been a faculty member at MIT since 1968, where he has been the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. His interests are focused on internal combustion engines, their fuels, and broader studies of future transportation technology, fuel supply options, and air pollutant and GHG emissions. He has published more than 200 papers in the technical literature and is the author of five books, including a major text and professional reference, *Internal Combustion Engine Fundamentals*. He is a fellow of the Society of Automotive Engineers. He has received many awards for his work, including the 1996 U.S. Department of Transportation Award for the Advancement of Motor Vehicle Research and Development and the Society of Automotive Engineers 2008 Award for his contributions to Automotive Policy. He is a member of the NAE and a fellow of the American Academy of Arts and Sciences. He has a Ph.D. from MIT, a D.Sc. from Cambridge University, and honorary degrees from Chalmers University of Technology, Sweden, and City University, London.

VIRGINIA McCONNELL is senior fellow in the Quality of the Environment Division of Resources for the Future (RFF), Inc. She is also a professor of economics at the University of Maryland, Baltimore County. Her recent work has centered on the evaluation of policies to reduce motor vehicle pollution, particularly on the role of pricing and other incentive-based policies. She recently completed a study on hybrid vehicles and the effectiveness of policies designed to increase the share of hybrids and electric vehicles in the U.S. fleet, part of a larger effort at RFF to assess a range of transportation and other policies to reduce oil use and GHG emissions in the United States by 2030. She was co-editor of the 2007 book *Controlling Vehicle Pollution* and has published on a range of transportation policy issues. In addition, she has served on a number of EPA and state advisory committees related to transportation and air quality. She is currently serving on a public policy panel to look at the prospects for Transport Electrification. She has been a member of several NRC panels in recent years, including the Committee on Vehicle Emission Inspection and Maintenance Program, the Committee on State Practices in Setting Mobile Source Emissions Standards, and the Committee for a Study of Potential Energy Savings and Greenhouse Gas Reductions from Transportation. Dr. McConnell received a B.S. degree in economics from Smith College and a Ph.D. degree in economics from the University of Maryland.

STEPHEN J. McGOVERN has more than 35 years of experience in the refining and petrochemical industries. Dr. McGovern has been a principal of PetroTech Consultants since 2000, providing consulting services on various refining technologies, including clean fuels projects and refining economics. He has assisted numerous refiners in the evaluation of gasoline and diesel desulfurization technologies, Catalytic Cracking and environmental issues. Dr. McGovern has provided technical advice to DARPA and commercial enterprises for the production of biofuels. Previously, he was with Mobil Technology Company, where he led various efforts in process development and refinery technical support. He has 17 patents and more than 20 technical publications and was a member of the NRC Committee on Economic and Environmental Impacts of Increasing Biofuels Production. He has lectured, published and consulted on refining technology, environmental and alternate fuels issues. Dr. McGovern is a licensed professional engineer in New Jersey and a past director of the Fuels and Petrochemicals Division of AIChE. He earned a B.S. degree (magna cum laude) and M.S. degree in chemical engineering from Drexel University and M.A. and Ph.D. degrees in chemical engineering from Princeton University.

GENE NEMANICH is a consultant specializing in chemical processes. Previously, he was director of hydrogen systems for ChevronTexaco Technology Ventures where he was responsible for hydrogen supply and developing and commercializing new hydrogen storage technologies. He has 31 years of experience with integrated oil companies, including Exxon, Cities Service, Texaco, and ChevronTexaco. He has also worked in the areas of refining, clean coal technology, oil supply and trading, and hydrogen systems. He represented Texaco in the California Fuel Cell Partnership in 2000-2001 and is a director of Texaco Ovonic Hydrogen Systems, LLC, a joint venture with Energy Conversion Devices to commercialize metal hydride hydrogen storage systems. He was one of seven industry leaders that helped prepare the DOE-sponsored Hydrogen Roadmap, and he has served as chairman of the National Hydrogen Association. He has a B.S. in chemical engineering from University of Illinois and an MBA from University of Houston.

JOHN O'DELL is senior editor with the Edmunds.com editorial team, where he originated online coverage of the environmental or "green" automotive segment, producing articles dealing with advanced and alternative vehicle policies, financing, technology, politics, alternative fuels, and related issues. Mr. O'Dell is regularly quoted by major newspapers, periodicals, wire services, and broadcast media as an expert on the growing green car and alternative fuels markets. Prior to joining Edmunds, Mr. O'Dell was a staff writer and editor at the *Los Angeles Times* from 1980-2007. He co-founded the consumer automotive section of the *L.A. Times*, Highway 1, in 1998, and was the paper's automotive industry reporter from 1998-2007. He also served variously as city beat reporter, county government writer, business reporter, and assistant business editor at the *Times' Orange County Edition* and was variously a city beat reporter, investigative reporter, political writer, and assistant city editor at the *Orange County Register*. Mr. O'Dell holds a B.A. in communications from California State College at Fullerton and completed the coursework there toward a graduate degree in communications with an emphasis in consumer economics. His career as a journalist has been marked by numerous awards for professional excellence in writing, research, and project development. He was part of the reporting teams that won Pulitzer prizes for the *Los Angeles Times* in 1992 for coverage of the Los Angeles Riots and in 1994 for coverage of the Northridge Earthquake.

ROBERT F. SAWYER (NAE) is the Class of 1935 Professor of Energy emeritus in the Department of Mechanical Engineering at the University of California, Berkeley. His research interests are in combustion, pollutant formation and control, regulatory policy, rocket propulsion, and fire safety. He served as chairman of the California Air Resources Board, chairman of the energy and resources group of the University of California at Berkeley, chief of the liquid systems analysis section at the U.S. Air Force Rocket Propulsion Laboratory, and president of the Combustion Institute. Dr. Sawyer has served on numerous National Research Council committees and was a member of the NRC's Board on Environmental Studies and Toxicology. He holds a B.S. and M.S. in mechanical engineering from Stanford University and a M.A. in aeronautical engineering and a Ph.D. in aerospace science from Princeton University.

CHRISTINE S. SLOANE retired from General Motors Corporation as the head of the global team for hydrogen and fuel cell vehicle codes and standards development. She coordinated development of GM policy and technical strategy across safety, engineering, and public policy requirements to ensure global consistency in GM interaction with government and professional industry organizations. She previously directed the GM interaction with the U.S. FreedomCAR program, which included R&D to advance fuel cell power systems, and earlier served as chief technologist for the development and demonstration team for Precept, GM's 80 mile-per-gallon five-passenger HEV concept vehicle. She has also been responsible for global climate issues and for mobile emission issues involving advanced technology vehicles. Her early research interests included air quality, and manufacturing and vehicle emissions. Dr. Sloane has authored more than 80 technical papers and co-edited one book. She has served on several boards of professional organizations and numerous National Academy of Sciences panels and study groups. Dr. Sloane received her Ph.D. from MIT in chemical physics.

WILLIAM H. WALSH, JR., is an automobile safety consultant. He consults on vehicle safety activities with several technology companies to speed the introduction of advanced life-saving technology into the automobile fleet as well as substantive involvement in corporate average fuel economy (CAFE) rulemakings. He held several positions at the U.S. National Highway Traffic Safety Administration (NHTSA), including senior associate administrator for policy and operations; associate administrator for plans and policy; director, National Center for Statistics and Analysis; director, Office of Budget, Planning and Policy; and science advisor to the administrator of NHTSA. He also held the position of supervisory general engineer at the DOE's Appliance Efficiency Program. His expertise covers all aspects of vehicle safety performance, cost/benefit analyses, strategic planning, statistics analyses and modeling, and policy formulation. He serves on the Transportation Research Board's Occupant Protection Committee. He has a B.S. in aerospace engineering, University of Notre Dame, and an M.S. in system engineering, George Washington University.

MICHAEL EVAN WEBBER is the Josey Centennial Fellow in Energy Resources, associate professor of mechanical engineering, associate director for the Center for International Energy and Environmental Policy, and co-director of the Clean Energy Incubator, all at the University of Texas at Austin. Previously he was an associate engineer at RAND Corporation and senior scientist at Pranalytica, Inc. He holds four patents involving instrumentation. He serves on the board of advisers of *Scientific American* and is on the editorial board of several other journals. Dr. Webber is also a member of the Electric Utility Commission of the City of Austin and is active in a variety of other public and civic organizations. He has an M.S. and Ph.D. in mechanical engineering (minor, electrical engineering) from Stanford University and B.S./B.A. degrees with high honors from the University of Texas at Austin.

C

Meetings and Presentations

FIRST COMMITTEE MEETING
OCTOBER 21-22, 2010, WASHINGTON, D.C.

Overview of DOE's Vehicle Technologies Program: Potential for Light Duty Vehicle Technologies NAS Study
Patrick Davis, U.S. Department of Energy

Vehicle Technologies Program (VTP): Analysis Briefing for NAS
Phillip Patterson and Jacob Ward, U. S. Department of Energy

FY2011 VTP Energy Storage R&D
David Howell, U.S. Department of Energy

Analysis Methods from Recent Studies
Robert Fri, U.S. Department of Energy

Transportation Energy Futures
Austin Brown, National Renewable Energy Laboratory

SECOND COMMITTEE MEETING
DECEMBER 14-15, 2010, WASHINGTON, D.C.

Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts
Mike Ramage, Consultant

Alternative Transportation Technologies: Hydrogen, Biofuels, Advanced ICEs, HEVs and PHEVs
Mike Ramage, Consultant

Perspectives on Energy Security and Transportation: The Intersection of National Security and Economic Challenges
Robbie Diamond, Electrification Coalition

Biofuels: Technology Status and Challenges
Andy Aden, National Renewable Energy Laboratory

EPA's Light-Duty Vehicle GHG Technical Activities
Bill Charmley, U.S. Environmental Protection Agency

THIRD COMMITTEE MEETING
FEBRUARY 1-2, 2011, WASHINGTON D.C.

BP Energy Outlook 2030
Mark Finley, BP

Reducing Greenhouse Gas Emissions from U.S. Transportation
David Greene, Howard H. Baker Center for Public Policy and Steve Plotkin, Argonne National Laboratory

Critical Materials Strategy
Diana Bauer, United States Department of Energy

Toward a New National Energy Policy: Assessing the Options
Alan Krupnick and Virginia McConnell, Resources for the Future

FOURTH COMMITTEE MEETING
MARCH 21-22, 2011, WASHINGTON, D.C.

ARPA-E's BEEST Program: Ultra-High Energy, Low Cost Energy Storage for Ubiquitous Electric Vehicles
David Danielson, ARPA-E

Carbon Capture and Storage RD&D
Jay Braitsch, U.S. Department of Energy

Future Transportation Fuels Study, National Petroleum Council
Linda Capuano, Marathon Oil Company

Overview of Hydrogen and Fuel Cells
Sunita Satyapal and Fred Joseck, U.S. Department of Energy

The Mercedes-Benz Hydrogen Roadmap
Sascha Simon, Mercedes Benz

FIFTH COMMITTEE MEETING
MAY 12-13, 2011, DETROIT, MICHIGAN

No open sessions were held during this meeting.

SIXTH COMMITTEE MEETING
JUNE 27-29, 2011, IRVINE, CALIFORNIA

Potential for Light-Duty Fuel Cell EVs, 2010-2050
Ben Knight, Honda

Alternative Fuel Strategy . . . As Seen by a Policy Wonk, Regulator, and Academic
Dan Sperling, University of California, Davis

Plug-in Electric Vehicles and their Impact to the Grid
Reiko Takemasa, Pacific Gas and Electric Company

ADDITIONAL COMMITTEE MEETINGS

The committee met in closed session for deliberations and report writing and review on the following dates: August 10-11, 2011; September 12, 2011; October 5-7, 2011; December 14-15, 2011; January 25-26, 2012; March 29-30, 2012; and May 15-16, 2012.

D

Reports on Transportation Greenhouse Gas Emissions Projections to 2050

Many studies have examined the potential for greenhouse gas (GHG) emissions reductions in the U.S. transportation sector. Summarized below are the key studies that the National Research Council (NRC) Committee on Transitions to Alternative Vehicles and Fuels considered in its analysis. They include broad impact studies, such as the NRC report *Real Prospects for Energy Efficiency in the United States* (NRC, 2009b) and the *Science* article “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies” (Pacala and Socolow, 2004), as well as studies focused on specific components of the transportation sector, such as the Transportation Research Board (TRB) report *Driving and the Built Environment: Effects of Compact Development on Motorized Travel, Energy Use, and* CO_2 *Emissions*. *Special Report 298* (2009), which focuses on compact land use as a mitigation strategy. This summary is meant merely to serve as context for the committee’s charge—it does not attempt to review the validity of any findings contained herein. Any assertions made in the text of this appendix represent findings in the respective reports, not judgments of the current committee.

D.1 REAL PROSPECTS FOR ENERGY EFFICIENCY IN THE UNITED STATES (NRC, 2009b)

The NRC project “America’s Energy Future: Technology Opportunities, Risks, and Tradeoffs” evaluated current contributions and the likely future impacts, including estimated costs, of existing and new energy technologies. The study looked at three time frames: today through 2035, 2035 through 2050, and beyond 2050.

In its transportation analysis in the report *Real Prospects for Energy Efficiency in the United States*, the panel reviewed how current technologies are likely to improve and, as a result, be deployed. It then constructed two scenarios of vehicle and technology deployment as a means of estimating the potential overall effects of improved passenger vehicles and technologies on fuel consumption and GHG emissions.

For its analysis, the panel first assessed the likely technological changes expected over the three time frames and estimated the relative changes that might be seen among vehicle types. It then applied estimates of possible deployments of vehicle types to determine the overall potential reduction in petroleum use and GHG emissions that might be possible in the time frames of interest. The tables and figures below show the results. More details are available in the report itself and in the reports referenced in the text, especially Bandivadekar et al. (2008).

D.1.1 Relative Petroleum Use and Greenhouse-Gas Emissions by Vehicle Type

Table D.1 estimates the potential relative petroleum use and emissions of different vehicle types, both current and projected out to 2035. These estimates are based on studies that evaluated the fuel-consumption reduction potential of plausible improvements in vehicle technologies, including alternative powertrains. Each entry in Table D.1 is the fuel consumption (in gasoline equivalent) relative to that of the average vehicle in either the current or 2035 new-vehicle sales mix.

TABLE D.1 Potential Relative Vehicle Petroleum Use and Greenhouse Gas Emissions from Vehicle Efficiency Improvements

	Petroleum Consumption (gasoline eq.)		Greenhouse Gas Emissions[a]	
Propulsion System	Relative to 2005 gasoline ICE	Relative to 2035 gasoline ICE	Relative to current gasoline ICE	Relative to 2035 gasoline ICE
2005 gasoline HEV	1.00	—	1.00	—
2005 turbocharged gasoline	0.90	—	0.90	—
2005 diesel	0.80	—	0.80	—
2005 hybrid electric vehicle (HEV)	0.75	—	0.75	—
2035 gasoline	0.65	1.00	0.65	1.00
2035 turbocharged gasoline	0.60	0.90	0.60	0.90
2035 diesel	0.55	0.85	0.55	0.85
2035 HEV	0.40	0.60	0.40	0.60
2035 plug-in hybrid (PHEV)	0.20	0.30	0.35-0.45	0.55-0.70
2035 battery electric vehicle (BEV)	None		0.35-0.50	0.55-0.80
2035 hydrogen fuel cell vehicle (HFCV)	None		0.30-0.40	0.45-0.60

NOTE: These estimates assume that vehicle performance (maximum acceleration and power-to-weight ratio) and size remain the same as today's average new-vehicle values. That is, the improvements in propulsion efficiency are used solely to decrease fuel consumption rather than to offset increases in vehicle performance and size. Estimates have been rounded to the nearest 0.05. BEVs and HFCVs are expected to have shorter driving ranges than PHEVs between rechargings or refuelings.

[a] Greenhouse gas emissions from the electricity used in 2035 PHEVs, 2035 BHEVs, and 2035 HFCVs are estimated from the projected U.S. average electricity grid mix in 2035 (Kromer and Heywood, 2008). Greenhouse gas emissions from hydrogen production are estimated for hydrogen produced from natural gas.

SOURCE: Bandivadekar et al. (2008). Estimates based on assessments by An and Santini (2004); Wohlecker et al. (2007); Cheah et al. (2007); NPC (2007); and NRC (2004).

These values assume fleet performance and interior size are essentially the same as those of vehicles coming out on the market today, although the load is reduced via lightweighting (20 percent weight reduction), aerodynamics (25 percent reduction in vehicle drag), and rolling resistance (33 percent reduction in tire rolling-friction coefficient). The values in the table are meant to represent what *could* be achieved, not what is likely to be achieved.

D.1.2 Incremental Purchase Cost by Vehicle Type

These fuel economy improvements are obtained at a premium. Table D.2 depicts the estimated increase in vehicle cost (compared to today's car and truck average prices for a new vehicle). These cost estimates are based on a number of studies examining current and future vehicle technology costs for manufacturers. An additional 40 percent mark-up is assumed to account for indirect costs, reflecting with the 1.4 retail price equivalent what a consumer would actually pay for the vehicle. However, different manufacturers may choose to subsidize particular technologies with different deployment strategies in mind, so these costs are subject to large uncertainty.

TABLE D.2 Estimated Additional Cost to Purchaser of Advanced Vehicles Relative to Baseline 2005 Average Gasoline Vehicles

	Additional Retail Price (2007 dollars)	
Propulsion System	Car	Light Truck
2005 gasoline ICEV	0	0
2005 diesel ICEV	1,700	2,100
2005 hybrid HEV	4,900	6,300
2035 gasoline ICEV	2,000	2,400
2035 diesel ICEV	3,600	4,500
2035 hybrid HEV	4,500	5,500
2035 PHEV	7,800	10,500
2035 BEV	16,000	24,000
2035 HFCV	7,300	10,000

NOTE: Costs listed are additional costs only, relative to baseline average new car and light truck purchase prices (in 2007 dollars) that were calculated as follows:

- Average new car: $14,000 production cost × 1.4 retail price equivalent = an average purchase price of $19,600; and
- Average new light truck: $15,000 × 1.4 = $21,000.

For the purpose of these estimates, the PHEV all-electric driving range is 30 miles; the BEV driving range is 200 miles. Advanced battery and fuel-cell system prices are based on target battery and fuel-cell costs.

SOURCE: Bandivadekar et al. (2008).

D.1.3 Deployment

Because these alternative powertrains are at an emerging stage of deployment, it is difficult to ascertain what the vehicle mix will look like in the future. For example, while the NRC report *Transitions to Alternative Transport Technologies: A Focus on Hydrogen* (NRC, 2008) concluded that up to 2 million hydrogen fuel cell vehicles (HFCVs) could be on the road by 2020, it is unlikely that such a rapid transformation would take place, given the infrastructural needs of a hydrogen-powered fleet.

Table D.3 is an attempt by the Committee on America's Energy Future to project what the *likely* future vehicle fleet mix could look like, focusing in particular on alternative powertrains. These numbers are for *new* sales only and do not represent the total fleet mix. The committee did not foresee significant deployment of plug-in hybrid electric vehicles (PHEVs), battery-powered electric vehicles (BEVs), or HFCVs without significant technical progress resulting in significant cost reduction below the levels indicated in Table D.2.

Table D.4 depicts how consumption would change given such a potential vehicle mix. The committee suggested that in the future, some of the reduction in fuel consumption for a fleet comprised of vehicles equivalent to today will be offset by changes in the fleet (increased vehicle performance, size, and weight). There are two scenarios—the first (optimistic) would meet the Corporate Average Fuel Economy (CAFE) standards outlined in Energy Independence and Security Act of 2007 (EISA 2007) (35 mpg by 2020), as required; the second (conservative) would see those standards delayed by 5 years and put less of an emphasis on fuel economy. Neither scenario considered BEVs or HFCVs. In both scenarios, advanced powertrains are imagined to make up more than half of the new vehicle fleet in 2035, resulting in the optimistic case of a 100 percent increase in fuel efficiency up to 50 mpg. For reference, the most recent proposed rule for the 2017-2025 model years (MYs) by the Environmental Protection Agency and the National Highway Traffic Safety Administration has a CAFE standard of 40.9 mpg by MY2021 with a conditional second phase leading to a 49.6 mpg fleet-wide average by MY2025.

TABLE D.3 Plausible Share of Advance Light-Duty Vehicles in the New-Vehicle Market by 2020 and 2035 (%)

Propulsion System	2020	2035
Turbocharged gasoline SI vehicles	10-15	25-35
Diesel vehicles	6-12	10-20
Gasoline hybrid vehicles	10-15	15-40
PHEV	1-3	7-15
HFCV	0-1	3-6
BEV	0-2	3-10

NOTE: The percentage of hydrogen fuel-cell vehicles considered “plausible” is in contrast to the percentages reported in *Transitions to Alternative Transport Technologies: A Focus on Hydrogen* (NRC, 2008), which represent “maximum practical” shares.

TABLE D.4 Illustrative Vehicle Sales Mix Scenarios

				Market Share by Power Train (percent)						
	% Emphasis on Reducing Fuel Consumption[a]	% Light Trucks vs. Cars	% Vehicle Weight Reduction	Naturally Aspirated SI	Turbo SI	Diesel	Hybrid	Plug-in Hybrid	Total Advanced Power Train	% Fuel Efficiency Increase from Today
Optimistic[b]										
2020	75	40	17	52	26	7	15	0	48	+38
2035	75	30	25	36	26	9	20	9	64	+100
Conservative[c]										
2025	50	40	17	55	24	7	14	0	45	+38
2035	50	40	20	49	21	7	16	7	51	+62

[a] The amount of the efficiency improvement that is dedicated to reducing fuel consumption (i.e., that is not offset by increases in vehicles power, size, and weight).

[b] The optimistic scenario meets the new CAFE target of 35 mpg in 2020, and then extrapolates this rate of improvement through 2035. In this case, the average fuel economy in 2035 reaches 52 mpg, roughly double today’s value.

[c] The conservative scenario achieves the new CAFE target of 35 mpg only in 2025 (5 years later) and extrapolates this rate of improvement through 2035, when the average fuel economy reaches only 60 percent above today’s value.

D.1.4 Cumulative Effects

Figure D.1 shows, for the conservative and optimistic scenarios, the corresponding annual gasoline consumption of the United States in-use light-duty vehicle (LDV) fleet from the present out to 2035. A no-change baseline assumes that all of the efficiency improvements go to vehicles size, weight, and power, as has occurred since 1982. The cumulative fuel savings under each scenario compared with this no-change baseline are indicated. Note that this no-change baseline includes some growth in overall fleet size and miles driven but no resulting change in vehicle fuel economy. No similar assessment is given for GHG emissions.

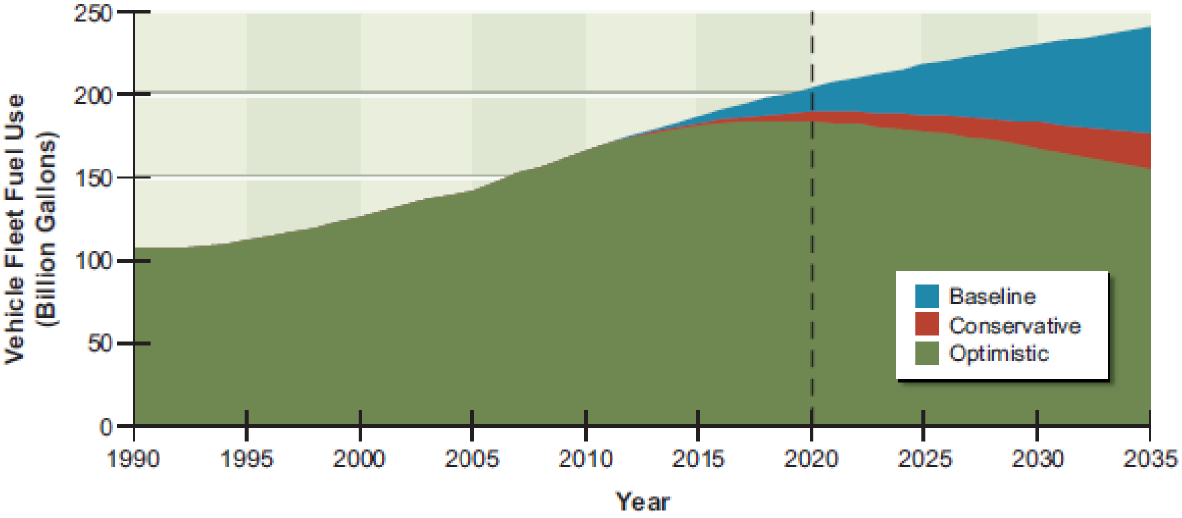

FIGURE D.1 Fuel use for the U.S. in-use light-duty vehicle fleet out to 2035.
SOURCE: Cheah and Heywood (2008).

D.2 LIQUID TRANSPORTATION FUELS FROM COAL AND BIOMASS—TECHNOLOGICAL STATUS, COSTS, AND ENVIRONMENTAL IMPACTS (NRC, 2009a)

The NRC committee examining America's energy future also looked into developments in the fuels sector related to conversion from coal and biomass. Below are the study's main findings as it pertains to the automotive sector.

Figure D.2 shows the estimated gasoline-equivalent costs of alternative liquid fuels produced from coal, biomass, or a combination of the two. The fuels would be produced by either biochemical conversion to ethanol, thermochemical conversion via Fischer-Tropsch, or thermochemical conversion via the methanol-to-gasoline process. Carbon capture and storage (CCS) could be used in either thermochemical conversion process to reduce GHG emissions, so the costs are shown both with and without CCS. Also shown for comparison are the prices for gasoline based on two different crude oil prices, (2007) $60 or (2007) $100 per barrel. At $60 per barrel, only the coal-to-liquid fuels are comparably priced. Even at $100 per barrel, biomass-to-liquid fuels are not cost competitive without carbon pricing.

Carbon pricing has a significant effect on competitiveness. The committee examined the costs with a carbon price of $50 per tonne (1,000 kg) CO_2-equivalent, and biomass-to-liquid fuels become cost competitive with standard gasoline at $100 per barrel crude oil. If CCS is added to the biomass-to-liquid plant, it becomes cost competitive by $80 per barrel crude oil, as does cellulosic ethanol.

The reason for this shift in competitiveness can be seen in Table D.5. Here is tabulated the committee's values for lifecycle emissions for the various fuels. Fuels generated from biomass have a net-negative emissions of CO_2 over the lifecycle of the fuel, where the lifecycle is defined from the harvesting of the fuel to its consumption.

In addition to examining the costs and benefits associated with alternative fuels, the committee studied its potential for deployment. Figure D.3 depicts the maximum potential build-up of cellulosic ethanol, one of the alternative fuels specified as part of the Renewable Fuel Standard 2 (RFS2). Two scenarios are shown in Figure D.3—the first (in blue) is the maximum build-up if it is assumed to be similar to that of grain ethanol; the second (in red) is a more aggressive scenario leading to approximately double the capacity of grain ethanol. Neither scenario is meant to be a prediction but a limit.

The build-up of cellulosic-ethanol is, like other biomass fuels, highly dependent on the prices of other fuels. However, if cellulosic-ethanol plants are shown to be commercially viable, cellulosic

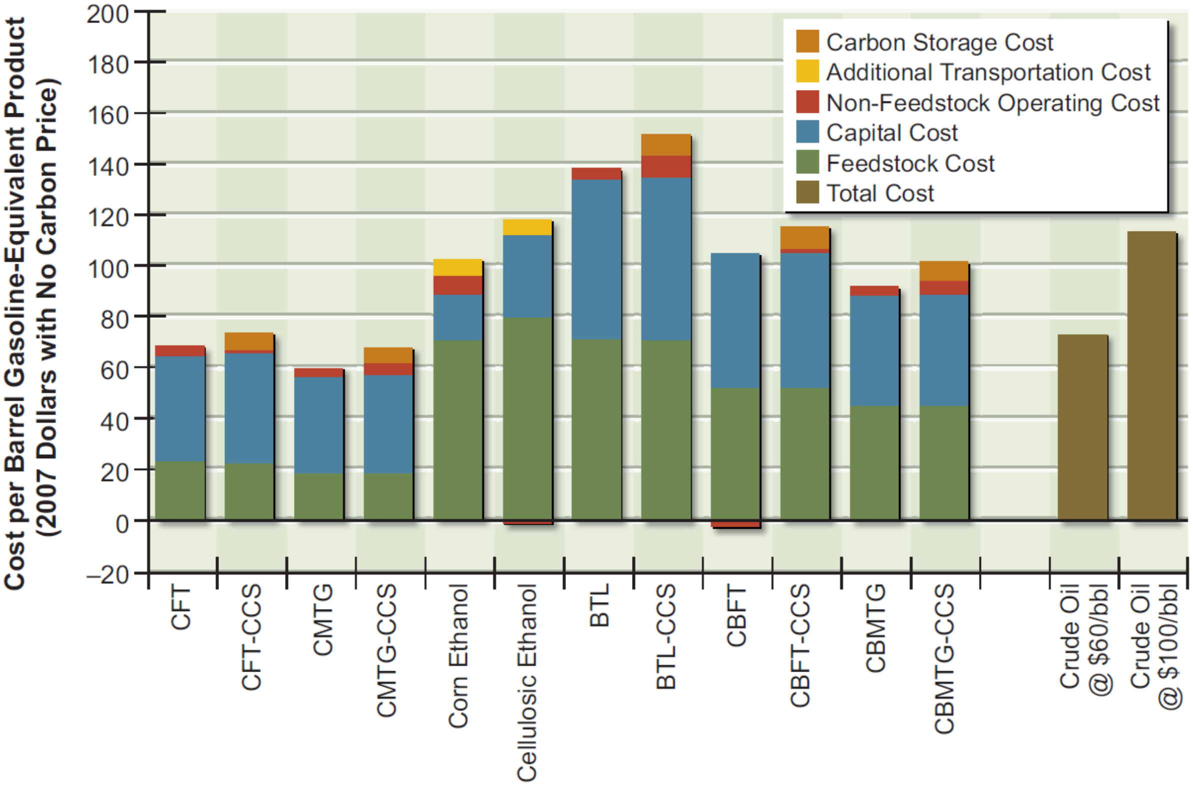

FIGURE D.2 Costs of alternative liquid fuels produced from coal and biomass assuming no carbon price. BTL = biomass-to-liquid fuel; CBFT = coal-and-biomass-to-liquid fuel, Fischer-Tropsch; CBMTG = coal-and-biomass-to-liquid fuel, methanol-to-gasoline; CCS = carbon capture and storage; CFT = coal-to-liquid fuel, Fischer-Tropsch; CMTG = coal-to-liquid fuel, methanol-to-gasoline.

TABLE D.5 Net CO_2 Emissions (tonnes per barrel gasoline eqivalent)

Fuel Type	Net CO_2
CFT	1.06
CFT-CCS	0.44
CMTG	1.10
CMTG-CCS	0.42
Corn ethanol	0.37
Cellulosic ethanol	−0.10
BTL	−0.13
BTL-CCS	−0.76
CBFT	0.49
CBFT-CCS	−0.21
CBMTG	0.47
CBMTG-CCS	−0.13
Gasoline	0.42

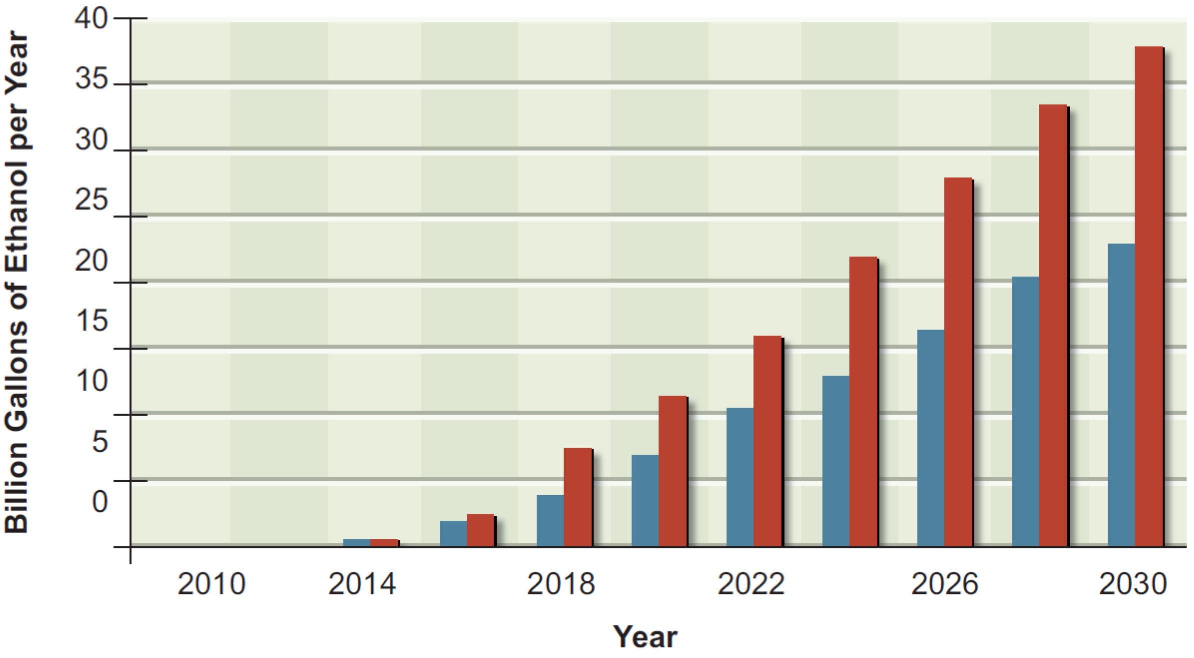

FIGURE D.3 Cellulosic-ethanol capacity-building scenarios starting with commercial demonstration plants in 2009 with first commercial-scale plants following thereafter, building to 1 billion gallons of cellulosic ethanol per year in 2015. Capacity-building beyond 2015 is in accordance with the maximum capacity build achieved for grain ethanol (blue bars) and a more aggressive capacity build of about twice that achieved for grain ethanol (red bars). The maximum build rate could achieve the 2022 RFS2 mandate of 16 billion gallons of cellulosic ethanol per year, but it would be a stretch.

ethanol could replace up to 0.5 million barrels of gasoline equivalent per day by 2020 and 1.7 million barrels per day by 2035. The necessary supply of tons of biomass per year of 440 million dry tons in 2035 would be only marginally larger than the estimated annual supply of 400 million dry tons of cellulosic biomass that could be produced sustainably with technologies and management practices available in 2008 and well short of the estimated 550 million dry tons that would be deliverable by 2020.

D.3 TRANSPORTATION'S ROLE IN REDUCING U.S. GREENHOUSE GAS EMISSIONS (DOT, 2010)

Under EISA 2007, the Department of Transportation (DOT) was required to report on the potential strategies for reducing GHG emissions within the transportation sector. Select results from this two-volume report are summarized below.

D.3.1 Alternative Fuels

Because this report was written during the rulemaking for the second generation of the Renewable Fuel Standard (RFS2), biofuels were excluded from analysis. However, numerous other alternatives to gasoline and diesel were given, including compressed natural gas (CNG), hydrogen, and electricity. The GHG emissions reductions for each of these fuels is summarized in Table D.6. Values for electricity as a "fuel" are calculated for BEVs with all-electric ranges of 100 and 200 miles. Fuel

TABLE D.6 Costs and Benefits for Alternative Fuels Out to 2030 to 2050

Fuel	Year	Incremental Vehicle Cost	Discounted Fuel Cost ($)	Net Discounted Cost/Savings	Average GHG Reduction (Tonnes/yr.)	Net Dollars per Tonne per Year
Compressed natural gas	2030	$3,000	−$4,460	−$1,460	0.7	−$132 to −$50
Hydrogen	2020	$10,000	−$3,500 to $4,400	$6,500 to $14,400	2.7	$151 to $333
	2030 to 2050	$1,500 to $5,300	−$11,900 to −$8,300	−$10,300 to −$3,000	3.3	−$199 to −$57
BEV100	2030	$6,000	−$11,300	−$3,500	3.1 to 3.7	−$90 to −$106
BEV200	2030	$10,200	−$11,300	−$1,100	3.1 to 3.7	−$19 to −$22

generated from fossil fuel products such as liquid propane, Fischer-Tropsch gas-to-diesel, and coal-to-liquid gasoline were also discussed but found to be too carbon intensive to be used to effect significant GHG reductions; in fact, in one cited example, an sport-utility vehicle (SUV) fueled with gasoline derived from coal released twice as much GHG emissions per mile compared to conventional fuel when you look at the entire fuel lifecycle. CCS would help eliminate some of the upstream GHG emissions, but the DOT study viewed this as still in the research and development (R&D) stage and did not include such features in its report.

A crucial question for the application of non-traditional fuels is the ability for vehicles using those fuels to penetrate the marketplace. In the case of natural gas, this report estimates that approximately 19 million vehicles could be fueled by CNG without significantly affecting the price and supply of domestic natural gas; furthermore, they cite an established infrastructure and current vehicle fleet as evidence of its potential for scalability. For hydrogen, because there is no established model for the vehicles or infrastructure, the estimates ranged from 93,000 by 2030 to 2 million vehicles on the road by 2025 at a cost of approximately $10 billion. Finally, electric vehicles were estimated to be as much as 9 percent of new vehicle sales in 2030, or approximately 10 million total vehicles on the road; however, this value is noted as highly speculative.

D.3.2 Vehicle Technologies

There were four main strategies considered to reduce GHG emissions from gasoline-powered LDVs, (1) advanced conventional gasoline engine technologies, (2) conversion to diesel, (3) hybrid electric vehicles (HEVs), and (4) PHEVs. The resultant GHG reductions and costs are shown in Table D.7. Hydrogen fuel cells were considered separately because they would require a transition to an alternative fuel.

In addition to technology that addresses fuel consumption, it is possible to reduce GHG emissions by addressing mobile air conditioning (MAC) systems. Current, MAC systems contribute approximately 3.5 percent of all LDV GHG emission. There are three approaches to reducing emissions associated with the operation of the MAC system: (1) reduce the leakage of the refrigerant to the atmosphere; (2) reduce the greenhouse warming potential of the refrigerant itself; and (3) reduce the engine load associated with running the air conditioning system. Alternative refrigerants would result in reductions of 91.3 to 99.9 percent. Reductions in engine load could reduce GHG emissions from MAC operation by as much as 30 percent.

TABLE D.7 Greenhouse Gas Reductions and Costs for the Implementation of Different Fuel Economy Technologies

Technology	Year	Conventional Vehicle MPGGE	Scenario MPG		GHG Emission Reduction Range		Average Incremental Vehicle Cost	
			Min.	Max.	Min.	Max.	Min.	Max.
Advanced ICE	2010	21.9	26.7	29.3	18%	25%	−$60	$2,399
	2030+	28.2	30.8	40.4	8%	30%		
Advanced diesel	2010	21.8	27.6	31.2	21%	29%	$1,567	$5,617
	2030+	28.2	28.2	33.2	0%	16%		
Hybrid electric vehicles	2010	21.8	26.2	53.9	17%	60%	$3,700	$5,700
	2030+	28.2	38.3	60.8	26%	54%	$2,300	$4,100
PHEV-10	2030	28.2			36%	60%	$3,100	
	2050				38%	62%	$2,900	
PHEV-40	2030	28.2			51%	70%	$6,100	
	2050				57%	74%	$5,300	
PHEV-60	2030	28.2			58%	74%	$8,100	
	2050				65%	74%	$6,900	

NOTE: PHEV values recalculated using the range of hybrid electric vehicle reductions from the table above instead of the nominal 40 percent used in the text. Utility factors for the PHEV-10, -40, and -60 are 0.23, 0.60, and 0.75, respectively.

D.3.3 Vehicle Miles Traveled Strategies

An alternative way to reduce fuel consumption by the transportation sector is to simply use vehicles less. There are numerous ways of reducing vehicle miles traveled (VMT)—among them are telecommuting, increased use of public transportation, compact land use, traffic management, and eco-driving. Implementing all of these potential strategies could result in a net GHG reduction of 12 to 30 percent by 2030 and 14 to 37 percent by 2050,[1] with the largest contribution coming from compact land use (2.5 to 7.8 percent in 2030 and 5.0 to 16 percent in 2050). Details of the strategies to improve system efficiency and reduce carbon-intensive travel activities can be found in DOT (2010) in Tables 3.5 and 3.6, respectively.

D.4 SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS (UCD, 2011)

The Institute for Transportation Studies (ITS) at the University of California, Davis, compiled its research on sustainable transportation pathways from 2007-2010. Its work focused on six main technology pathways moving forward: biofuels; advanced, efficient internal combustion engines (ICEs); HEVs; PHEVs; BEVs; and HFCVs. The report looked at the costs of these technologies, the challenges facing implementation of these technologies, their ability to reduce GHG emissions, and policy options that could be used to push these technologies into the mainstream in order to reduce GHG emissions.

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[1] Tables 3.5 and 3.6 in Volume 1 show the cost effectiveness of GHG emission reductions by reducing VMT of the light-duty vehicle fleet by 2030. Combined reductions are treated as multiplicative so as to not overcount.

D.4.1 Technology Costs

The ITS researchers calculated costs for each advanced vehicle technology in 2030 and compared them to a 2007 baseline, port-injected gasoline vehicle (27.1 mpg). They found that advanced ICE technology offers an extremely cost-effective path to obtain a 43 percent reduction in fuel consumption, with a break-even fuel price of $3.62/gallon.[2] They looked at a range of battery and hydrogen fuel cell prices to examine the potential for novel technologies to make a significant impact. Although hybrid vehicles require a small battery, it is a small component of the cost of the vehicle, and because of its 33 percent reduction in consumption beyond that of the advanced ICE vehicle (ICEV), the advanced hybrid vehicle has a break-even cost of $2.29-$2.61/gallon. According to the ITS analysis, the PHEV-40 offers the greatest potential for energy savings at 79 percent; however, at $500/kWh the break-even cost is $5.29, and it does not slip below $4 unless the battery price comes down to $300/kWh. HFCVs offer a similar fuel benefit, but because of the additional cost of hydrogen as a fuel source, the break-even cost is $4.02/gallon for a $50/kW fuel cell and $2.86/gallon if the $30/kW fuel cell target set by the Department of Energy (DOE) is met. According to the ITS report, BEVs would require $5/gallon gasoline to break even, even for a battery at $300/kWh, due to the extremely high costs of the lithium-ion (Li-ion) battery.

D.4.2 Requirements for Deployment

In order to understand the barriers facing a transition to any of the advanced fuels (hydrogen, electricity, biofuels), the ITS researchers examined the capability of fueling 10 percent of the LDV fleet with these fuels.

D.4.2.1 Hydrogen

Supporting 10 percent of the LDV fleet would require approximately 250,000 kg of platinum (Pt), more than the current world annual production. It is likely, therefore, that platinum recycling would be necessary and add to the cost of hydrogen deployment. Additionally, because the initial deployment of hydrogen as a fuel is almost certainly going to be derived from natural gas, about 3 percent of the total natural gas in use today would be needed to generate the required 5 billion kg of hydrogen. Most of the hydrogen is expected to be reformed on site, although approximately 9,000 miles of pipeline centered in urban areas would be required. The investment necessary to support such a fleet size would be $38 billion: $21 billion would be used for the 14,000 onsite reformers, $4 billion for biomass plants with CCS, $9 billion for pipeline, and $4 billion for pipeline stations.

D.4.2.2 Electricity

For a 10 percent fraction of the country's LDVs, approximately 28 GW of night-time energy would be necessary, or less than 5 percent of the U.S. generation capacity. Over the course of the next 40 years, it is also expected that the grid will become become greener. While major system upgrades are unlikely to be necessary, there may be a need for local "smart grid" interfaces. The largest deployment cost is going to in home chargers, which are estimated at $800-$2,100 per installation. Summed over 10 percent of the total LDV fleet, this would require an investment of $16 billion to $42 billion. There may be additional infrastructure required for fast charging at waypoints.

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[2] Break-even gas prices are calculated based on a 5-year return with a 4 percent discount rate and an average VMT of 12,000 miles per year.

D.4.2.3 Biofuels

To fully fuel 10 percent of the LDV fleet with biofuels would require about 12 billion gallons of gasoline equivalent per year. This, in turn, would be derived primarily from corn (requiring ~30 percent of the current annual supply) and forest, agricultural, and municipal wastes. To distribute the biofuels, an additional 7,000 rail tank cars would be required. If the fuels produced are drop-in fuels, no additional infrastructure is required for fueling; however, if it is entirely ethanol, 20,000 E85 stations would be required to support 20 million vehicles. $50 billion to $70 billion would be required in total, with 80 percent of that for biorefineries (150 corn ethanol plants, 76 cellulosic biorefineries, and/or 16 biodiesel plants) and the remainder to support the biofuel delivery system.

D.4.3 Scenarios to Reduce Greenhouse Gas Emissions

Looking forward to 2050, the researchers at ITS came up with three types of future scenarios: (1) the business-as-usual (BAU) scenario; (2) "silver bullet" scenarios, where an individual technology is deployed as aggressively as possible; and (3) "deep-reduction" scenarios, where a combination of technologies are deployed in tandem to maximize the reductions in GHGs.

D.4.3.1 Reference Scenario

The reference scenario is dependent on a 69 percent population increase, significant increase (102 percent) in per-capita transport demand (mostly due to an expansion of air-based travel), and moderate efficiency improvement (45 percent, or about 1 percent each year). In the LDV fleet, these efficiency improvements would result in a fleetwide fuel economy of 35 mpg by 2050. The carbon intensity of the grid remains essential the same as 1990 levels, owing to the presumed continued dominance of carbon-based fuels. Any improvements in carbon intensity from the increased blending of biofuels into gasoline is offset by the increased usage of unconventional fossil fuel sources such as oil sands. In this scenario, domestic GHG emissions from the transportation would increase by 82 percent.

D.4.3.2 Silver Bullet Scenarios

The available technologies have been described in USD (2010). Figure D.4 depicts the GHG emissions with full deployment of each technology. It is clear that no single technology can meet even the 50 percent reduction in GHG emissions from 1990—in fact, only one (a 50 percent reduction in average VMT across the transportation sector, with an increased use of mass transit and high-density land use) even breaks even with 1990 levels. In the hydrogen-intensive scenario, low-carbon hydrogen production (24.3 gCO_2e/MJ) is assumed, and HFCVs make up 60 percent of the fleet. In the electricity-intensive scenario, the carbon intensity of the grid is assumed to be reduced by 79 percent below 1990 values, and the fleet is presumed to be composed of half BEVs and half PHEVs in 2050.

D.4.3.3 Deep-Reduction Scenarios

The study focused on three deep-reduction scenarios: (1) U.S. Efficient Biofuels 50in50, which looks at a deep penetration of biofuels and improved efficiency; (2) U.S. Electric Drive 50in50, which focuses on widespread adoption of BEVs, PHEVs, and HFCVs; and (3) U.S. Multi-Strategy 80in50, which effectively combines the two 50in50 plans. Assumptions of the three plans are shown in Table D.8,

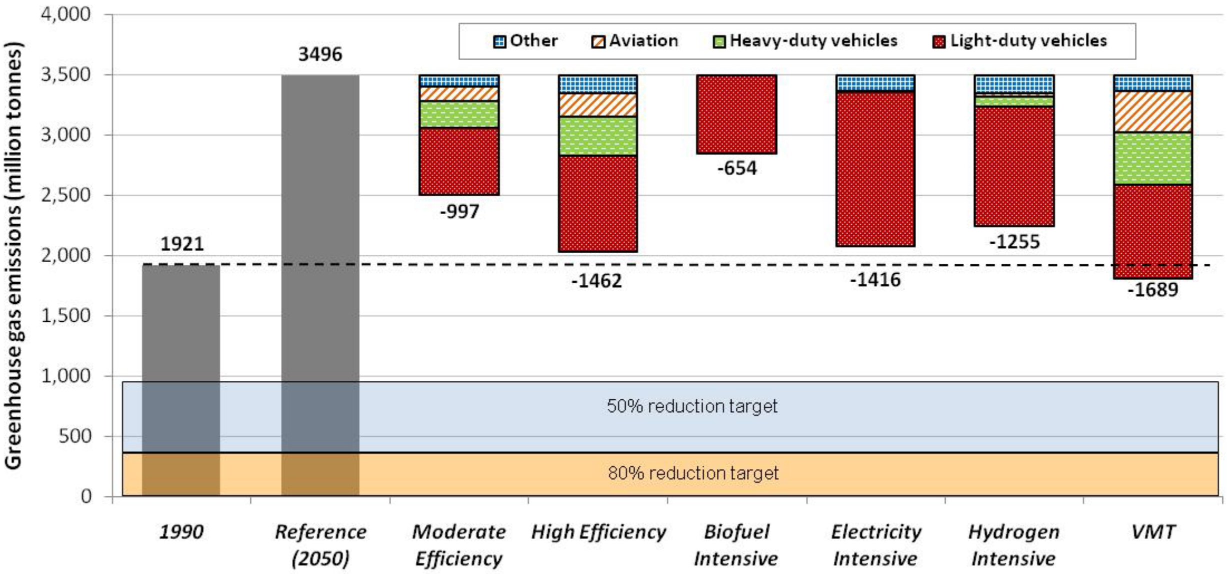

FIGURE D.4 Greenhouse gas (GHG) emissions for the transportation sector in 2050 for scenarios with the widespread implementation of various GHG-reducing strategies. 1990 levels and the BAU reference case are shown for comparison. SOURCE: McCollum and Yang (2009).

and the results for the three scenarios are shown in Figure D.5. In outlining these deep-reduction scenarios, there are implicit changes in fuel generation as well such as a cleaner grid and low-carbon-intensity hydrogen production in order to achieve the results depicted in Figure D.5.

All scenarios involve a significant reduction in VMT. Somewhat counterintuitively, increased vehicle efficiency (due to the efficiency of electric motors and hydrogen-powered engines) in the Electric Drive scenario actually reduces fuel usage beyond the Efficient Biofuel scenario. In all cases, biofuels are used to reduce emissions from the expected increase in air travel; however, concerns about the availability of feedstock does raise uncertainty in its application. In fact, the Multi-Strategy 80in50 scenario would require 1.8 billion dry tons of biomass to produce both hydrogen (with CCS) for LDVs and the biofuels necessary to replace all aviation fuel. For shifting a large fraction of fuel to the electrical grid, an increasing diversity of natural resources (wind, solar) is more than adequate.

D.4.4 Policy Options for GHG Emissions

Policy will likely play a major role in enacting any of the transformative scenarios described in the previous section. In particular, ITS examined how cap-and-trade both economywide and in the transportation sector can play a role in driving these scenarios. They also explored the potential ramifications of a biofuel mandate and, conversely, a lack of cellulosic biofuels.

The results of the ITS study are shown in Figure D.6. The scenarios studied include a CO_2 emission cap of 10 percent, 20 percent, and 30 percent in both transportation and economywide; a 30 percent economywide and transportation cap without a complementary biofuel mandate and/or without access to biofuels; and a 40 percent and 50 percent economywide cap on CO_2 emissions. A major result in all studies is the complete lack of hydrogen vehicle penetration—the authors note, however, that hydrogen penetration is particularly sensitive to the cost of fuel cell technology, oil price, and discount rate assumed. By comparing the scenarios with and without a biofuel mandate, it is clear that ethanol use in the fleet for flex-fuel vehicles is driven by a mandate; however, looking at the fuel mix results, ethanol still can have significant penetration, even without a mandate. It can also be shown that biofuels are not a necessary component of meeting an emissions cap, although without biofuels available, cumulative fuel usage must decrease substantially compared to other scenarios, requiring significantly more efficient vehicles. In all scenarios, whether or not the transportation sector is specifically capped, the largest reduction in CO_2 emissions comes from a greening of the electric grid.

TABLE D.8 Assumptions for the Three Deep-Reduction Scenarios for U.S. Domestic Emissions in 2050

	Shares of Miles by Fuel Type				Normalized Transport Intensity (1990=100%)	Normalized Energy Intensity (1990=100%)	Normalized Carbon Intensity (1990=100%)
	Petroleum	Biofuels	Hydrogen	Electricity			
U.S.-Efficient Biofuels 50 in 50							
LDV	0	100	0	0	137	33	13
HDV	80	20	0	0	149	52	82
Aviation	100	0	0	0	234	36	100
Rail	84	0	0	16	171	59	80
Marine/Ag/off-road	100	0	0	0	117	40	101
All subsectors combined	35	64	0	1	152	37	53
Fuel demand (billion GGE)	77.2	88.5	0.0	1.3			
Carbon intensity (gCO2e/MJ)	90-96	12.3	-	44			
U.S.-Electric Drive 50 in 50							
LDV	10	0	60	30	137	24	40
HDV	72	0	22	5	149	60	100
Aviation	20	75	5	0	234	37	32
Rail	0	0	0	100	171	38	43
Marine/Ag/off-road	62	0	38	0	117	40	78
All subsectors combined	17	17	42	24	152	33	59
Fuel demand (billion GGE)	64.6	21.2	42.2	19.7			
Carbon intensity (gCO2e/MJ)	90-96	12.3	24	44			
U.S.-Multi-Strategy 80 in 50							
LDV	0	10	60	30	137	22	30
HDV	0	63	28	9	149	58	19
Aviation	0	100	0	0	234	37	14
Rail	0	0	0	100	171	38	43
Marine/Ag/off-road	2	79	20	0	117	40	28
All subsectors combined	0	36	40	24	152	32	24
Fuel demand (billion GGE)	1.9	82.3	39.3	19.1			
Carbon intensity (gCO2e/MJ)	90-96	12.3	24	44			

NOTE: Shown are the transport, energy, and carbon intensities as well as the share of transport miles for each fuel type/technology.

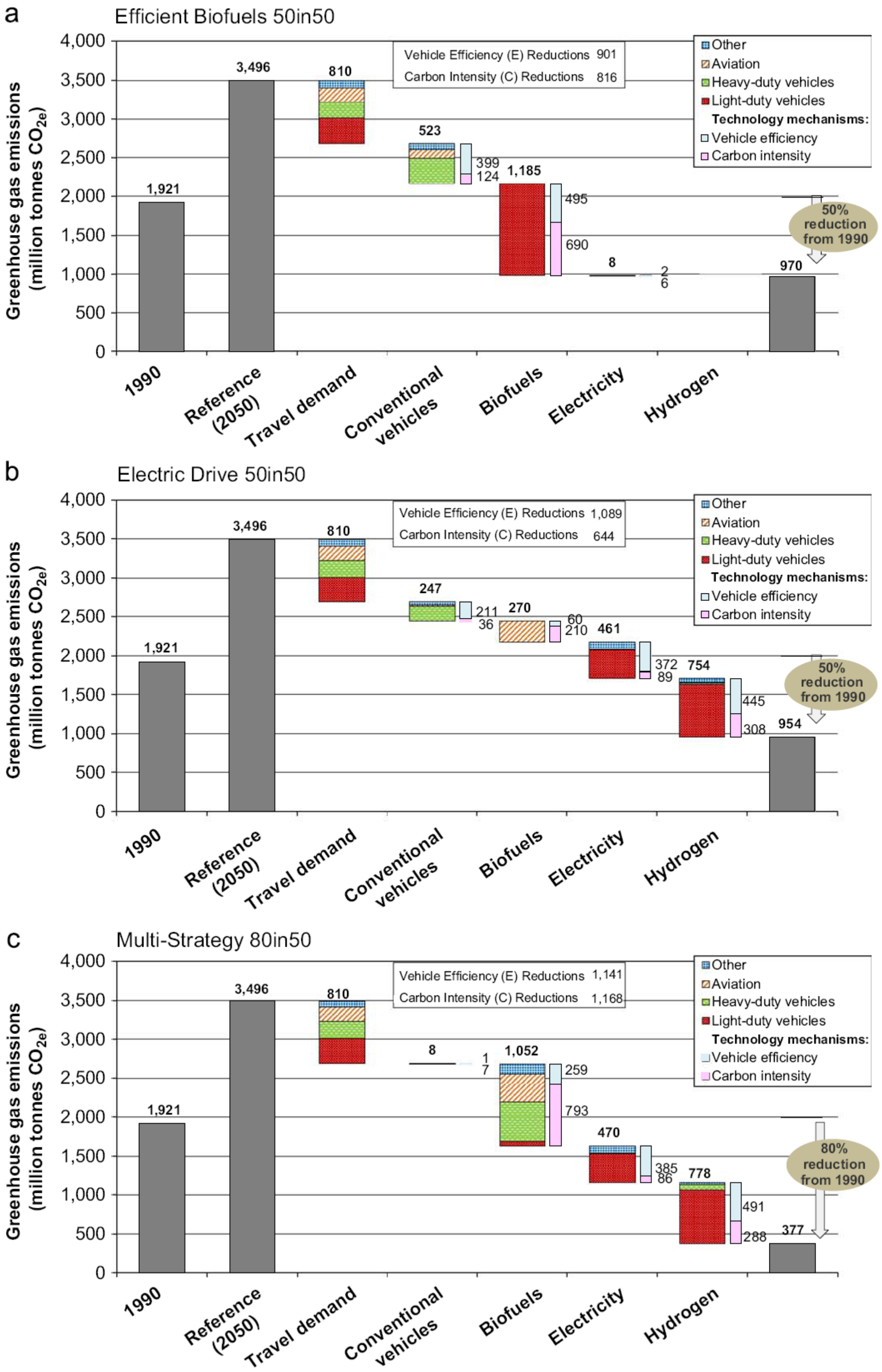

FIGURE D.5 Greenhouse gas emissions for the transportation sector in 2050 for deep-reduction scenarios. SOURCE: McCollum and Yang (2009).

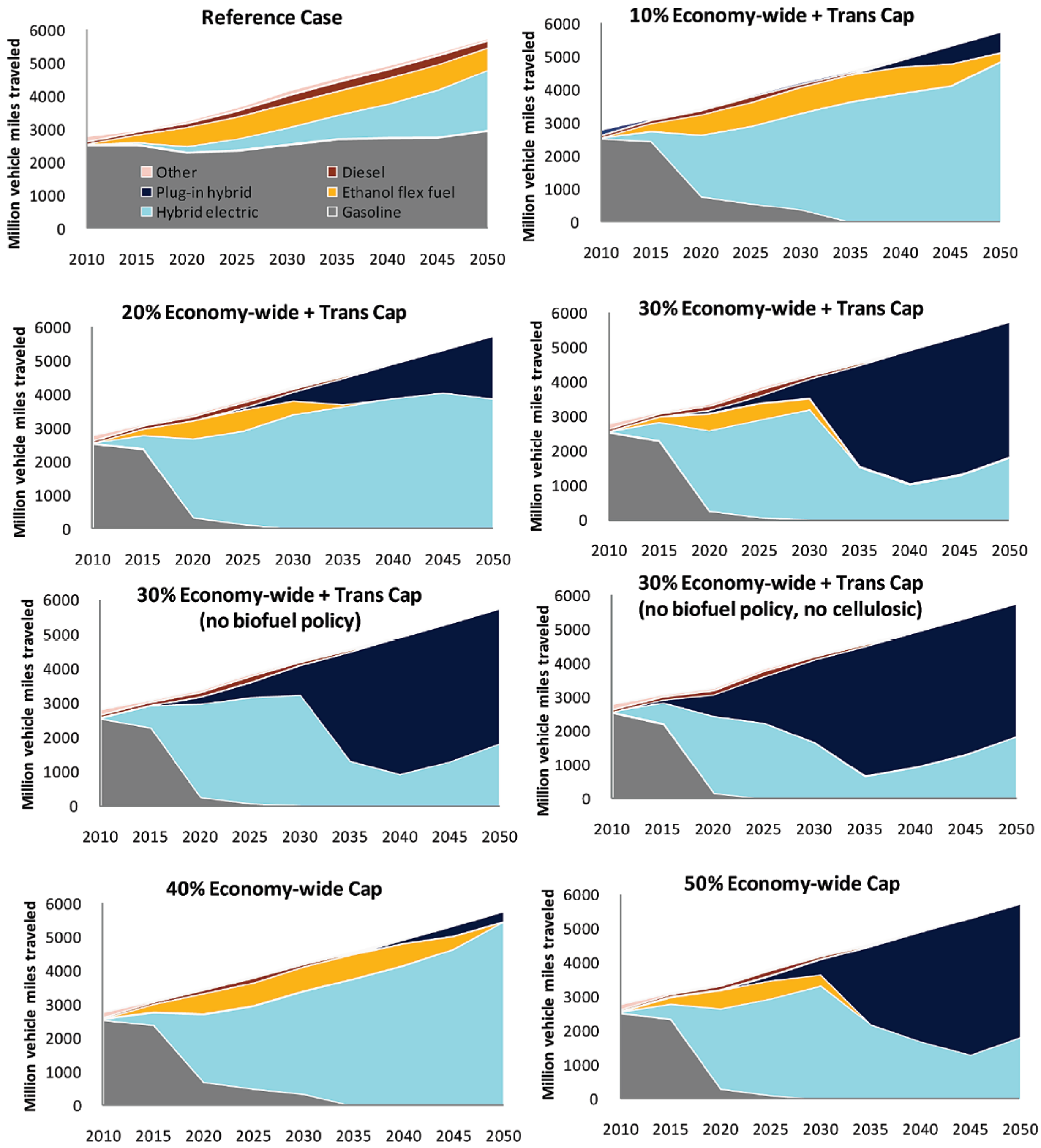

FIGURE D.6 Vehicle miles traveled for various vehicle technologies over time under different cap-and-trade scenarios.

D.5 LIMITING THE MAGNITUDE OF FUTURE CLIMATE CHANGE (NRC, 2010a)

The America’s Climate Choices Panel on Limiting the Magnitude of Climate Change was charged to describe, analyze, and assess strategies for reducing the net future human influence on climate, including both technology and policy options. The panel’s report focuses on actions to reduce domestic GHG emissions and other human drivers of climate change, such as changes in land use. As part of its analysis, it examined the energy demand from the transportation sector.

Shifting to low-carbon fuels provides one path to a reduction of GHG emissions. While there are vehicle technologies available that are already in use and could be rapidly deployed over the next decade (e.g., cylinder deactivation and direct injection), alternative-powertrain vehicles (PHEVs, HFCVs, BEVs) could provide a more significant reduction in GHG emissions by shifting away from gasoline as a primary fuel. However, in the case of electric vehicles, shifting the fuel source to the grid would require a decarbonization of the grid to make a significant impact. New natural gas plants can compete with new coal plants thanks to the plummeting costs of natural gas, and it emits about half the CO_2. A 12-20 percent increase in U.S. nuclear capacity is possible by 2020—this, too, would help decarbonize the grid and provide a low-GHG fuel for vehicles. Finally, biofuels offer significant potential for a low-carbon fuel source. There is no technological limit to expansion out to 2020 using current technologies, but a high level of deployment may result in significant barriers. Furthermore, while new technologies such as cellulosic ethanol provide an even lower-GHG alternative, there is significant uncertainty in its feasibility.

Reducing the VMT is another way to decrease GHG emissions. Urban development focused on mixed-use and aimed to make alternative modes of travel more feasible is one strategy for reducing VMT and thus CO_2 emissions. TRB recently examined this question of whether petroleum use and GHG emissions could be reduced by changes in development patterns. Below is a brief overview of some key findings from TRB (2010).

In order to reduce VMT, it is not enough to increase population and employment densities. While this does lead to shorter trips and better supports public transit, it is generally insufficient to significantly reduce VMT. Providing good connectivity between locations and accommodating non-vehicular travel is also important. The effects of compact development will differ depending on where it takes place: increasing density in established inner suburbs and urban core areas is likely to produce substantially more VMT reduction than developing more densely at the urban fringe.

The TRB committee developed a number of scenarios to estimate the potential effects of mixed-use development on reductions in energy consumption and CO_2 emissions**.** A “best case” scenario (with 75 percent of new housing units steered into more compact development and residents of compact communities driving 25 percent less) could lead to reduced VMT and associated fuel use and CO_2 emissions by about 7-8 percent less than the base case by 2030 and 8-11 percent less by 2050. A more moderate scenario (with 25 percent of new housing units built in more compact development and residents of those developments driving 12 percent less) could lead to in reductions in fuel use and CO_2 emissions of about 1 percent by 2030, and 1.3 to 1.7 percent by 2050. Committee members disagreed about whether the changes in development patterns and public policies necessary to achieve the high end of these findings are plausible.

In order to reduce heavy-duty/freight VMT, it may be possible to divert shipments from truck to rail travel. Rail transport is 5 to 15 times more energy efficient than truck per ton-mile. About 5 to 10 percent of truck traffic may be candidates for additional movement by rail. The greatest potential would be for shipments going more than 500 miles, although many carriers are already making this transition.

D.6 DRIVING AND THE BUILT ENVIRONMENT (TRB, 2010)

This study focused on the extent to which developing more compactly could reduce VMT and make alternative modes of travel more feasible. It is focused on metropolitan areas and personal travel, the two areas in which policy changes are likely to have the greatest effect. In addition to surveying the body of literature on VMT and compact land use, the committee conducted its own analysis of two scenarios. The first scenario is a plausible case of diverting 25 percent of all new housing developments to more compact mixed-use developments, where “compact” is defined as a doubling in density. The second scenario is a much more optimistic, policy-driven case that steers 75 percent of new and replacement housing units into more compact developments. The resulting reductions in CO_2 emissions for the higher density case are compared to the baseline projections in Figure D.7.

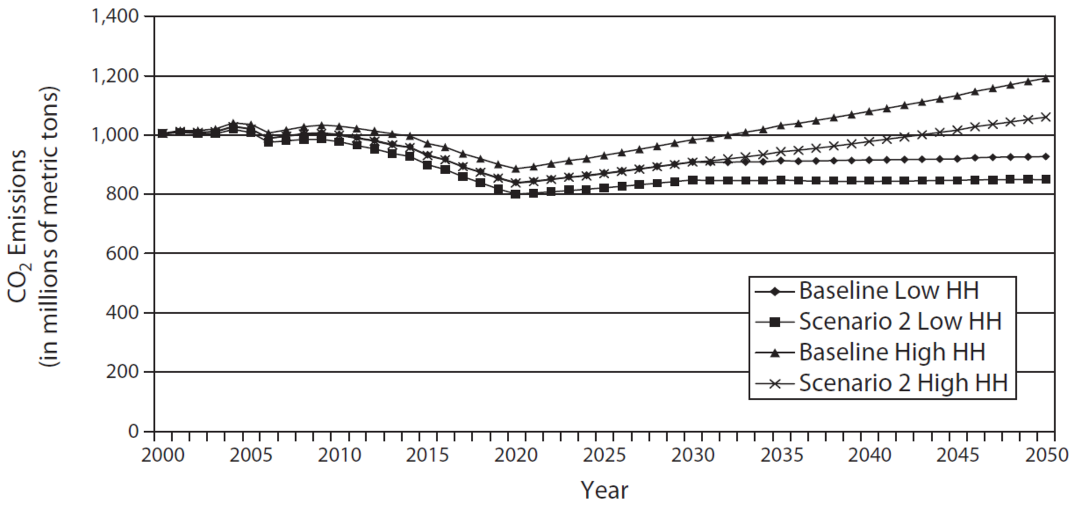

FIGURE D.7 Reduction in CO_2 emissions for low to high range of households (HH) from baseline in 2000-2050, assuming 75 percent of all new growth is compact, mixed-use development.

The low and high household values reflect the uncertainty in predicting population growth and replacement housing needs out to 2050. The committee estimates that the number of new housing units would be between 62 million and 105 million units by 2050—this compares to the housing stock of 105.2 million in 2000. The committee assumed no changes to the vehicle fleet beyond the standard proposed in EISA 2007; however, they did run sensitivity analyses to test a doubling of fuel economy by 2050 and found no change in the percent reduction between each scenario. The committee did find that significant fuel economy reductions would far outstrip a reduction in CO_2 emissions from VMT only.

Density is likely to lead to changes in vehicle mix and driving conditions that could affect the relationship of VMT to energy use and CO_2 emissions. For example, there is evidence that density will encourage the purchase of smaller and hence more fuel-efficient vehicles, so that the reduction in energy use may be more than proportionate to the reduction in VMT. Density may also increase stop-and-go driving and lower speeds under more congested conditions in higher-density areas, which would increase fuel consumption per VMT for conventional vehicles. Such behavioral changes may affect the results; however, the committee believes that these differences are captured in the uncertainties. Final results of the simulations for both scenarios and the baseline are summarized in Table D.9.

D.7 REDUCING GREENHOUSE GAS EMISSIONS FROM U.S. TRANSPORTATION (GREENE AND PLOTKIN, 2011)

This report looks at three scenarios for GHG reduction in the transportation sector. Key technology and policy assumptions for the scenarios as well as the results are described below.

D.7.1 Advanced Vehicles

Building largely on the work of the Massachusetts Institute of Technology report *On the Road in 2035* (Bandivedkar et al., 2008), the authors make a case for technological development that could be achieved: new passenger cars could attain 42.8 on-road mpg for gasoline-fueled engines with conventional drivetrains, 48.0 mpg with turbocharging, and 75.9 mpg with hybrid drivetrains. Equivalent values for light-duty trucks are 27.3 mpg, 32.2 mpg, and 49.0 mpg, respectively. The key question in each

TABLE D.9 Assumptions and Results for 2000-2050 Scenarios

	Baseline	25% New Housing	75% New Housing
Assumptions			
Housing Units (2000) [#]	105.2 million		
Housing Units (2050) [#]	152.9-190.0 million		
VMT per household (existing development)	21,187	21,187	21,187
VMT per household (new noncompact dev.)		+8.4% 22,967	+17.5% 24,895
VMT per household (new compact dev.)		−12% 20,211	−25% 18,671
Results			
% Increase in VMT between 2000 and 2050	50.2%-100%	48.3%-87.7%	42.6%-78%
VMT (in billions of miles) 2000 2050	2,228.9 3,348.5-4,458.6	2,228.9 3,305.5-4,182.8	2,228.9 3,177.4-3966.8
% change in 2050 VMT compared to base case		−1.3% to −1.7%	−8.4% to −11.0%

NOTE: Two scenarios are shown (25 percent of new housing at twice the average density and 75 percent of new housing at twice the average density) as well as the baseline projection.

of their proposed scenarios is the degree to which these improvements are made, because while these improvements may be technically achievable, historically most of the efficiency improvements have been nullified by increased performance and additional vehicle mass.

In order to reach the highest levels of fuel efficiency considered in the maximum reductions scenario, alternatively fueled vehicles must be considered. A large number of possible scenarios are conceivable, whether the fuel mix would involve a transition to biofuels, electricity, hydrogen, or a mixture of all three. For biofuel availability, the authors estimate as much as 60 billion gallons could be produced annually in 2050. In the case of electricity, the report cautions against battery electric vehicles due to costs and range anxiety, estimating instead as many as 20 million PHEVs on the road by 2050. With hydrogen, an infrastructure must also be put in place. One clear concern about any of these fuels is that in order to reach significant reduction, they must be generated with low-GHG emissions. For biofuels, this would entail careful tracking of indirect land use change and lifecycle emissions; for electricity, this would mean a shift to a “clean” grid, along with any necessary policies to induce such a shift; for hydrogen, this could mean biomass and coal with CCS instead of steam methane reforming.

D.7.2 System Efficiency

Improving system efficiency offers the potential for significant percent reductions in GHG emissions. However, there is significant debate over the effectiveness of these policies, given the unknown future public response. The authors describe a number of policies to improve system efficiency and reduce GHGs. They estimate that improvements in traffic flow would likely lead to between 0.5 and

1 percent reduction. Reduced trips from ridesharing and car-sharing programs utilized by 1 percent of the population yield GHG emission reduction potentials of 0.2 to 0.6 percent and 0.3 percent, respectively. While ecodriving could improve fuel economy for the average driver by about 10 percent, it is difficult to know to what degree these fuel efficient behaviors would manifest themselves in the public as a whole. Driver awareness also lends itself to proper maintenance, such as maintaining appropriate tire pressure, which could improve total on-road fuel economy by 0.3 percent. Increasingly compact land use is often touted as way to improve efficiency, but this is also the policy with the greatest barriers. The authors find that with appropriate policies, as much as 5 percent reductions in GHG emissions would be possible by 2050, although this would require the greatest acceptance among the public and is only suggested for the "High Reduction" strategy.

D.7.3 Policies to Promote Mitigation

Because GHG emissions reduction is a "public good," the market will not adequately capture any desired changes unforced. Thus, in order to reduce GHG emissions, policies are necessary. The policies and assumptions of the effectiveness of these policies are outlined in Table D.10. Policies such as fuel economy standards (like CAFE) and fuel standards (e.g., Low Carbon Fuel Standard, Renewable Fuel Standard) may be modeled after programs that are currently in place in this country. However, some of these policies need further clarification.

The main effect of a pricing policy is to suppress demand for a product. It may also be used to incorporate an external cost that the market does not account for. A carbon price of $25 per ton would raise the price of gasoline about 8 percent, reducing vehicle travel by 0.8 percent. Raising the price of fuel by pricing carbon also acts to increase demand for more fuel-efficient vehicles; thus, it can act as a complementary policy to fuel economy standards, encouraging consumers to purchase the vehicles manufacturers are required to make. Pay-as-you-drive insurance is an insurance mechanism that would charge based on the number of miles driven, thus encouraging operators to drive less; pay-at-the-pump has a similar effect but would charge as a function of energy usage and, therefore, encourages more efficient driving as well. Feebates are another way of promoting efficiency—a target vehicle fuel efficiency is set by a governing authority, and those vehicles that surpass it receive a rebate, while those that fall below this efficiency will be assessed a fee, both commensurate with the degree to which they exceed/fall short of the standard. Typically such a program is designed to be revenue-neutral. Because the goal of such policies is to improve the efficiency of vehicles traveling on U.S. roads, it is also important that the highways remain adequately funded as users travel a greater number of miles for a given amount of fuel. Currently, taxes have remained fixed per gallon of gasoline for decades. One way of ensuring a stable revenue source is to index the fuel tax to the efficiency of vehicles on the road.

Results of the scenarios involving the implementation of policies described above are shown in Figure D.8. By 2050, the High, Mid, and Low mitigation scenarios lead to a net decrease of GHG emissions from the transportation sector of 65 percent, 39 percent, and 16 percent, respectively.

D.8 POLICY OPTIONS FOR REDUCING ENERGY USE AND GREENHOUSE GAS EMISSIONS FROM U.S. TRANSPORTATION (TRB, 2011)

Like the study described in the previous section, this TRB study examines policy options across the entire transportation sector; however, it does not describe the implementation of particular levels of policy. In addition to sector-specific policies, the study first explores the effect of economywide carbon pricing. According to several economic models, each employing different assumptions about the costs of developing and deploying emissions-reducing technologies, prices starting at $25 to $75 per CO_2-equivalent tonne (CO_2e-t) and increasing to $225 to $500 per CO_2e-t would be required to achieve an 80 percent reduction in emissions economywide by 2050 (Fawcett et al., 2009). Such a carbon price would

TABLE D.10 Summary of Key Assumptions for Light-Duty Vehicles for the Low, Mid, and High Greenhouse Gas Emissions Mitigation Scenarios

	AEO 2010 (2010-2035)	2035			2050		
		Low	Mid	High	Low	Mid	High
Change in energy efficiency for total stock (miles per gallon)	*39%*						
Fuel economy/emissions standards, %		15.00	30.00	40.00	35.00	60.00	80.00
Driver behavior and maintenance, %		2.50	5.00	10.00	2.50	5.00	10.00
Improved traffic flow, %		0.00	1.00	2.00	0.00	1.00	2.00
Pricing policies							
Carbon price, %		2.44	2.44	2.44	3.57	3.57	3.57
Road user tax on energy, %		0.94	1.55	1.88	2.23	2.23	2.23
Pay at the pump insurance, %		0.00	4.37	4.37	0.00	5.20	5.20
Feebates, %		0.00	10.00	10.00	0.00	10.00	10.00
Automated highways, %		0.00	0.00	1.00	0.00	0.00	5.00
Change in vehicle miles traveled (billion vehicle miles traveled)	*54%*						
Road user tax on energy, %		−0.19	−0.49	−0.64	−0.39	−0.77	−1.03
Carbon price, %		−1.20	−1.20	−1.20	−1.74	−1.74	−1.74
Pay at the pump insurance, %		0.00	−0.97	−0.97	0.00	−0.97	−0.97
Trip planning and route efficiency, %		0.00	−2.00	−4.00	0.00	−5.00	−10.00
Ridesharing, %		0.00	−0.70	−1.40	0.00	−1.00	−2.00
Land use and infrastructure development, %		0.50	−1.00	−2.00	−1.50	−3.00	−5.00
Change in fuel carbon intensity for total stock (gCO_2e/MJ)	*−7%*						
LCFS: 2035 / increased hydrogen and electricity: 2050, %		−5.00	−10.00	−15.00	−5.00	−10.00	−47.22

NOTE: The percent change for the Annual Energy Outlook (AEO) 2010 BAU Case from 2010 to 2035 is shown in italics. Values shown in the table reflect percent changes from the AEO value for implementing the respective option. To compare the 2050 values, the AEO 2010 BAU scenario was extrapolated out to 2050 by the authors of the report.

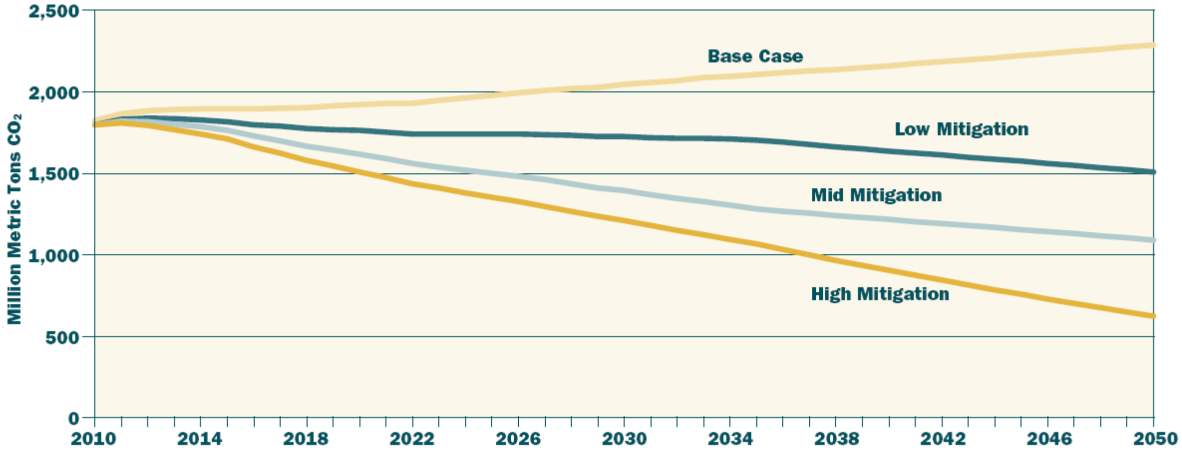

FIGURE D.8 Greenhouse gas emissions from the U.S. transportation sector for different policy scenarios.

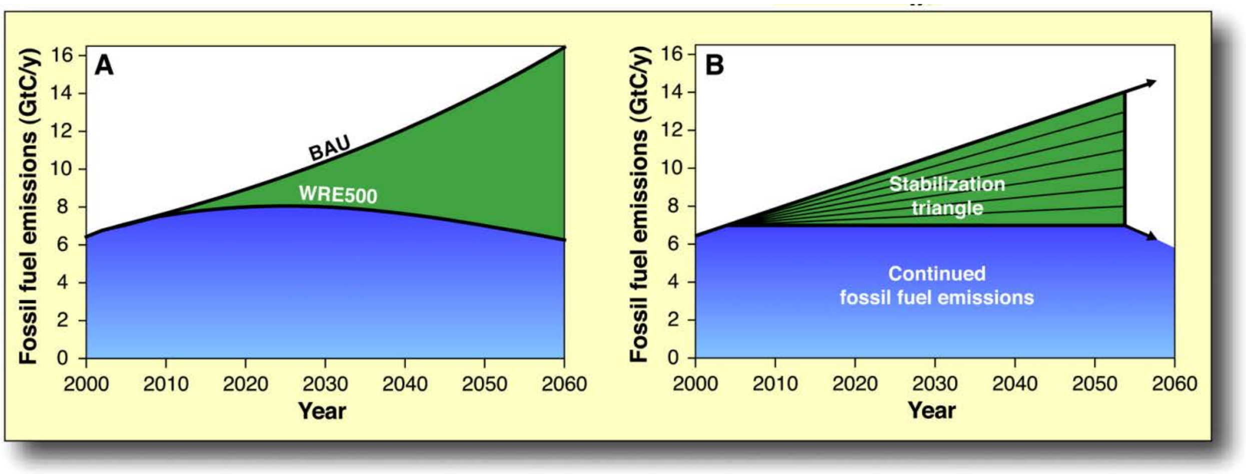

FIGURE D.9 (a) The top curve is a representative emissions pathway, in this case an annual growth of GHG of 1.5 percent. The lower curve models a scenario where GHG emissions would stabilize. (b) is an idealization of (a). The triangle is then broken up into wedges of equal area, each representing a reduction in carbon of 1 gigaton per year.

result in a approximately 20 percent reduction in emissions from the transportation sector alone. However, they also recognize the steep costs this would entail for electricity as well as in the LDV sector, where gasoline prices would be expected to increase about \$0.01/gallon per \$1/CO_2e-t.

D.9 STABILIZATION WEDGES: SOLVING THE CLIMATE PROBLEM FOR THE NEXT 50 YEARS WITH CURRENT TECHNOLOGIES (PACALA AND SOCOLOW, 2004)

The authors of this *Science* article outline tangible steps the world can take to reduce its fossil fuel emissions modeled on what they term “stabilization wedges” as shown in Figure D.9. There are several suggested activities in the paper—four of them are directly applicable to transportation emissions. Before detailing the strategies, it should be pointed out that these are approaches to mitigating GHG emissions—there are no price-tags associated with these strategies, nor are they meant to be a predictor of the transportation sector of 2054.

D.9.1 Efficient Vehicles

Citing a growth rate of 2.4 percent, the article estimates that in 50 years there will be roughly 2 billion cars on the road globally. If these gasoline-powered vehicles continue to average 10,000 miles per year as they do today, a doubling of fuel economy from 30 mpg to 60 mpg would correspond to the 1 gigaton reduction in carbon emissions necessary for a wedge. The level of fuel economy necessary to reduce GHG emissions by 1 gigaton is highly dependent on the initial level of fuel economy in the base case. If instead of 30 mpg the average fleetwide fuel economy today were 24 mpg, then the entire fleet would only need to achieve 40 mpg in 2050 to achieve a reduction of 1 gigaton of carbon.

D.9.2 Reduced Use of Vehicles

If instead these 2 billion 30-mpg cars reduced their VMT from 10,000 to 5,000 miles, this would also correspond to a 1 gigaton reduction in carbon emissions. Reducing the VMT by such a significant number would likely result in a modal shift towards mass transit, however, which (being another wedge) may result in double-counting of emissions.

D.9.3 Hydrogen-Powered Vehicles

Hydrogen-fueled vehicles offer a low-carbon alternative to gasoline-powered vehicles, enough so that a full transition to a hydrogen-powered fleet provides another wedge of opportunity. However, the way in which the hydrogen fuel is produced determines how much of an offset a complete transition to hydrogen-fueled vehicles yields. The most common mode of generating hydrogen today is part of the fossil-fuel power generation process. However, unless this is combined with carbon sequestration, this is too carbon-rich to provide enough of an offset.

An alternative production mechanism for producing hydrogen is via electrolysis. In this case, however, the authors found that the carbon emissions reductions from using carbon-free electricity that displaces coal and natural gas power plants were significantly larger than using this carbon-free electricity that displaces gasoline and diesel.

D.9.4 Biomass Fuel for Fossil Fuel

The displacement of carbon-rich fossil fuel with biofuels offers another potential wedge. It would require the production of about 34 million barrels per day of ethanol in 2054. This corresponds to roughly 250 million hectares of high-yield plantations (15 dry tons/hectare), or about one-sixth of the world's cropland. This may be an underestimate to the extent that biofuels require fossil fuel inputs. Because land suitable for annually harvested biofuel crops is also often suitable for conventional agriculture, biofuel production could compromise agricultural productivity. This is, however, a more efficient reduction in carbon emissions possible than if that same land were to be used as a carbon sink.

D.10 TRANSITIONS TO ALTERNATIVE TRANSPORTATION TECHNOLOGIES—A FOCUS ON HYDROGEN (NRC, 2008)

This study looks at the maximum practical number of HFCVs that could be deployed in 2020 and beyond. The committee concluded that "it would not be feasible to have enough hydrogen vehicles on the road by 2020 to significantly affect CO_2 emissions and oil use" (p. 3) and thus extended its timeframe out to 2050.

D.10.1 Hydrogen Production

In order to fuel a large hydrogen-powered fleet, hydrogen production will have to be significantly increased. The committee examined four means of producing hydrogen: (1) distributed steam methane reformation (DSMR) using natural gas, (2) centralized hydrogen production from coal gasification, (3) centralized production from biomass gasification, and (4) electrolysis. DSMR from natural gas for onsite production at a refueling station offers an economical first fuel for HFCVs, and even without carbon capture and sequestration (CSS) the well-to-wheels CO_2 emissions would be less than half that of a gasoline-powered automobile. However, the cost of DSMR is significantly dependent on the price of

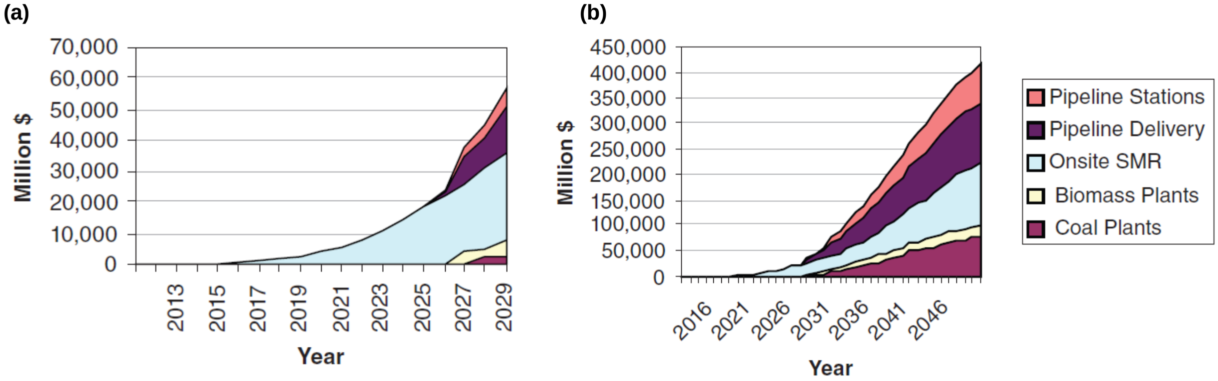

FIGURE D.10 Capital costs for hydrogen infrastructure out to 2030 (a) and 2050 (b).

natural gas, and just 50 million hydrogen-powered vehicles (less than 20 percent of the current fleet) would require a 10 percent increase in natural gas production if it was all generated via DSMR. Centralized hydrogen from coal gasification would require CCS to have a significant impact on CO_2 emissions, which also increases its costs. Biomass gasification has much lower emissions than coal, and combined with CCS it would be negative; however, the committee expressed concerns about it being an unproven technology with limits on availability (citing 500 million dry tons, or about 37 billion gallons of gasoline equivalent, 26 percent of the gasoline market). Finally, electrolysis was deemed too expensive to be used in any significant capacity, although the technology is available now. Infrastructure costs associated with these fuels are shown in Figure D.10.

D.10.2 Hydrogen Fuel Cell Vehicles

Because manufacturers have been working on prototype and preproduction HFCVs for a number of years, the committee believes that it is simply a matter of time before hydrogen vehicles are on the market. However, there are still a few technological hurdles to overcome, namely the high cost associated with platinum use in the fuel stack, fuel stack lifetime, and on-board storage. However, based on the amount of R&D money being pumped into HFCV projects, the committee expects full commercialization in the future. The cost for a hydrogen vehicle is shown in Figure D.11a. It is expected that the hefty price tag associated with a hydrogen vehicle would be subsidized by the manufacturer or the government in order to get the market price down to its fully learned out cost. Fuel costs are expected to be competitive with gasoline on a similar time frame (Figure D.11b). This is expected to lead to a practicable penetration rate of 20 percent of new vehicles by 2035 and 80 percent by 2050, leading to almost 2 million HFCVs on the road in 2020, 60 million in 2035, and more than 200 million in 2050.

D.10.3 Alternative Vehicle Technologies

There are three main paths for reducing gasoline usage proposed in this report: (1) efficiency, (2) HEVs, and (3) biofuels. Via conventional vehicle technologies (including but not limited to lightweighting, aerodynamics, and transmission upgrades), the report estimates that “evolutionary vehicle technologies could, if focused on vehicle efficiency, reduce fuel consumption by 2.6 percent per year through 2025, 1.7 percent per year in the 2025-2035 time frame, and 0.5 percent per year between 2035-2050” (p. 49), resulting in a net decrease in fuel consumption of 48 percent by 2050. Although the committee examined the use of HEVs, they did not consider PHEVs or BEVs to be a sufficiently established technology to develop a framework for analysis (see Section D.11 for a follow-up report). Hybrid vehicles were assumed to maintain their additional 29 percent reduction in fuel consumption

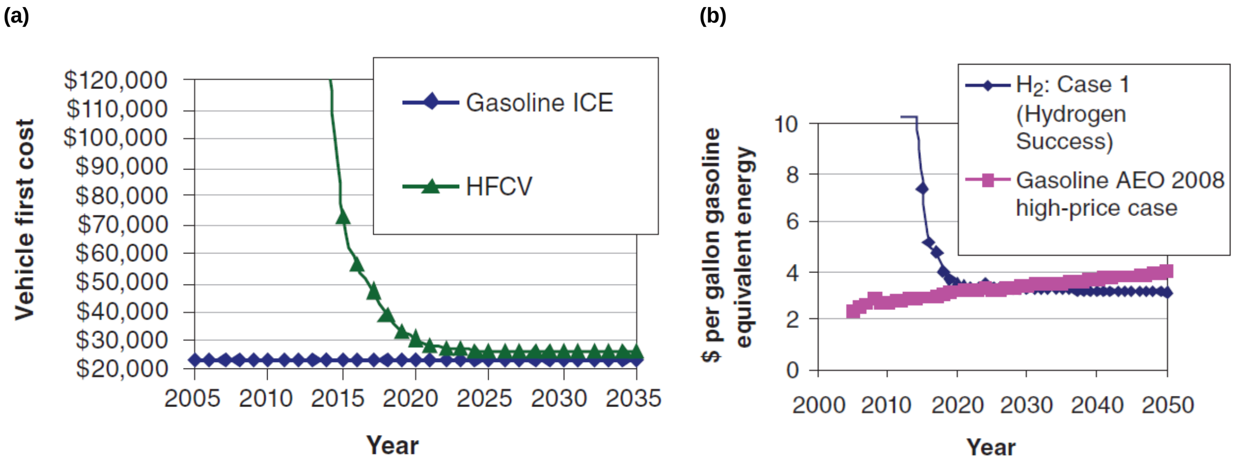

FIGURE D.11 Costs for hydrogen vehicle (a) and fuel (b) compared to gasoline equivalent.

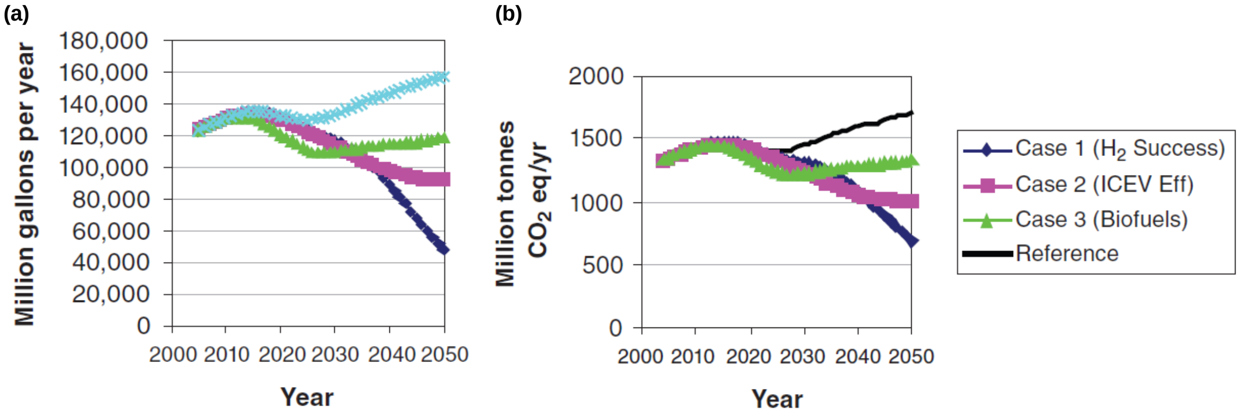

FIGURE D.12 (a) Millions of gallons of oil per year and (b) millions of tonnes CO_2 equivalent per year for each of the three scenarios (HFCVs, efficiency, and biofuels).

relative to comparable evolutionary conventional ICEVs. For biofuels, the main concern of the committee was, again, price and availability. The committee estimated that 335 million dry tons per year would be available in the near-term, 490 million dry tons per year by 2030, and as much as 700 million dry tons per year by 2050, although this would require significant technological advancement and potentially high-priced feedstock. This would result in an upper bound of 63 billion gallons of ethanol producible in 2050.

D.10.4 Greenhouse Gas Emissions

The committee examined three scenarios that offered substantial CO_2 emissions reductions by 2050: (1) HFCVs, (2) improved vehicle efficiency (including HEVs), and (3) biofuels. Figure D.12 shows reduction in oil (panel a) and GHG emissions (panel b) for each of these scenarios.

In addition to these scenarios, combinations of technologies were also examined. For example, a combination of efficiency and biofuels yields similar oil and GHG reductions to the HFCV case. Final results for all studies are shown in Table D.11.

TABLE D.11 Gasoline Displacement and GHG Emission Reductions for All Cases Compared to Reference

	Billion Gallons Gasoline Saved/yr (%)			Millions Tonnes CO_2 Avoided (%)		
Scenario	2020	2035	2050	2020	2035	2050
HFCVs	1.0 (0.8%)	34 (24%)	109 (69%)	10 (0.7%)	295 (19%)	1026 (60%)
Efficiency	2.2 (1.7%)	35 (25%)	64 (41%)	24 (1.7%)	385 (25%)	700 (41%)
HFCVs + Efficiency	3.0 (2.2%)	55 (39%)	125 (80%)	26 (1.8%)	475 (31%)	1123 (66%)
Biofuels	12 (9%)	28 (20%)	39 (25%)	118 (8%)	281 (18%)	386 (23%)
Efficiency + Biofuels	14 (11%)	64 (45%)	103 (66%)	143 (10%)	666 (44%)	1086 (64%)
Portfolio (All Options)	15 (11%)	83 (59%)	157 (100%)	130 (9%)	747 (49%)	1505 (88%)

TABLE D.12 Estimated Future Incremental (Compared to Nonhybrid) Costs of PHEVs (to the Manufacturer)

	2011	2015	2020	2030
PHEV-40	14,100-18,100	11,200-14,200	9,600-12,200	8,800-11,000
PHEV-10	5,500-6,300	4,600-5,200	4,100-4,500	3,700-4,100

D.11 TRANSITIONS TO ALTERNATIVE TRANSPORTATION TECHNOLOGIES—PLUG-IN HYBRID ELECTRIC VEHICLES (NRC, 2010b)

PHEVs were not included in the original analysis of this committee (NRC, 2008; see Section D.10) because of the speculative nature of any discussion regarding this emerging technology. However, this follow-on study returned to that issue to study the impacts of PHEVs within the scenarios outlined above. Here the committee considered two types of PHEV—a Toyota Prius-like PHEV with an all-electric range of 10 miles (which will be abbreviated as PHEV-10) and a Chevrolet Volt analog with an all-electric range of 40 miles (PHEV-40). The PHEV-10 has a smaller electric motor, so the gasoline engine is engaged in high-power situations as well as when the vehicle is running in charge-sustaining mode (similar to standard hybrid operation). In contrast, the PHEV-40 only runs in charge-sustaining mode when the battery has been fully depleted.

D.11.1 Battery Packs for PHEVs

Because Li-ion battery technology is well-adopted in the consumer electronics market (cell phones, laptop batteries, etc.), the committee felt that the steep drop in price typically associated with volume-based learning would not occur for the PHEV battery packs, leading to a slow reduction in price over time (Table D.12). The committee further noted that while breakthroughs in battery technology offer the potential to greatly lower the cost, it is not clear what sorts of breakthroughs may occur and, even if they did, whether they would be able to have much impact by 2030. While simply increasing the available state of charge (SOC) from 50 to 80 percent would lower the cost of the battery substantially, it was felt that there were significant potential risks to the longevity and safety of the battery, so the committee did not include changes to the available SOC in their cost reductions.

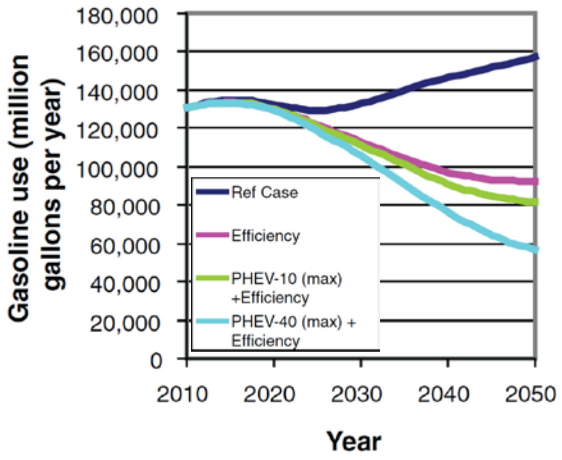

FIGURE D.13 Gasoline use for PHEV scenarios.

D.11.2 Market Penetration

Because of the high cost of batteries, the committee expressed concern over the ability for PHEVs to penetrate the market. They put forward two scenarios—the first is the probable market penetration, without subsidization and giveaways; the second is the maximum possible penetration of PHEVs, which would require policy initiatives such as subsidies, fuel economy standards, or carbon pricing. In the probable scenario, 3 percent of new vehicles sold in 2020 and 15 percent in 2035 would be PHEVs, leading to 110 million PHEVs on the road by 2050. This rate of penetration was determined by selecting the “probable” incremental costs of PHEVs, which do not find a payback period for PHEVs within a timeframe appropriate for the consumer, given gasoline prices less than $4 per gallon. In the maximum practical scenario, the committee used the same maximum sales rate as in the previous study for HFCVs (see Section D.10), resulting in a fleet of approximately 240 million PHEVs by 2050. Here they assumed the lowest anticipated future costs, noting that “if costs fail to decline to those levels, this scenario would be prohibitively expensive” (p. 24).

D.11.3 Petroleum and Greenhouse Gas Reductions

A PHEV gets its fuel economy benefits from the fact that the vehicle is using an electric motor for a substantial fraction of its mileage. However, GHG emissions from the vehicle are only reduced if the upstream emissions from the power plants acting as a “fuel source” for this battery are cleaner than the gasoline it is displacing. To analyze the potential GHG reductions under widespread PHEV adoption, the committee considered a number of different scenarios, as in the previous study (see Section D.10.4), as well as two different projected electrical grids, a BAU grid from the Energy Information Administration (EIA) and a “clean grid” adapted from the Electric Power Research Institute (EPRI) and the National Resource Defense Council (NRDC).

In the case of the PHEV-10, the vehicle runs 81 percent of its miles on the gasoline engine, meaning that it does not result in significant petroleum reductions compared to a normal HEV (just 7 percent additional reduction). This is reflected in Figure D.13, which compares the maximum practical PHEV-10 and PHEV-40 scenarios with the base efficiency and reference cases. Here the PHEV scenarios are combined with the efficiency case under the assumption that PHEVs would not make significant market gains until other efficiency measures have been enacted because of the costs associated with implementing this technology in the fleet.

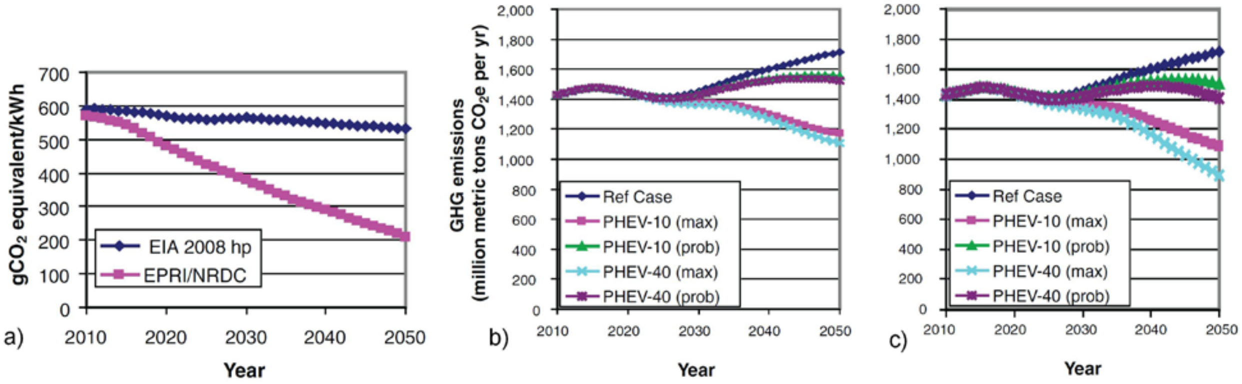

FIGURE D.14 (a) Comparison of the Energy Information Administration (EIA) business-as-usual grid and the Electric Power Research Institute (EPRI)/National Resource Defense Council (NRDC) clean grid. Greenhouse gas (GHG) emissions for the PHEV scenarios are shown for the two grids: (b) EIA BAU grid (2050: PHEV-10 max = 1170 Mmt CO_2, PHEV-40 max = 1100 Mmt CO_2); (c) EPRI/NRDC clean grid (2050: PHEV-10 max = 1090 Mmt CO_2, PHEV-40 max = 890 Mmt CO_2).

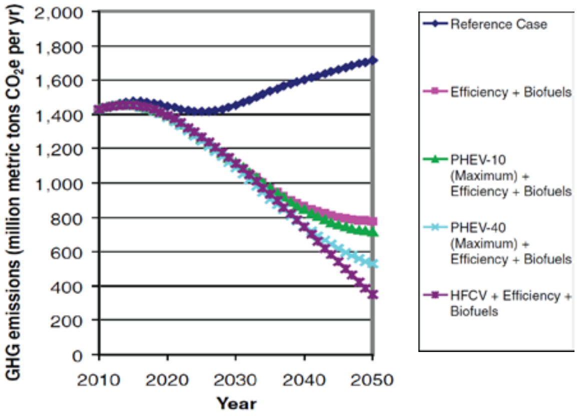

FIGURE D.15 Comparison of maximum practicable PHEV scenarios with biofuels and efficiency, in the clean grid case.

The significance of the grid in adoption of PHEVs is shown in Figure D.14. A cleaner grid increases the spread in the PHEV-10 and PHEV-40 emissions because of the higher fraction of VMT on electricity (19 percent for the PHEV-10 and 55 percent for the PHEV-40) and increases the available decrease in GHG emissions for the PHEV-40 (PHEV-10) from 35 percent (31 percent) to 48 percent (36 percent) by 2050.

The maximum practicable scenario for a clean grid, efficiency, and biofuels is shown in Figure D.15. Here it is also compared to the hydrogen case (Section D.10) with similarly available technologies. While efficiency and biofuels alone make up the majority of the reductions in all cases by 2050 (55 percent), PHEV-10s (59 percent) and PHEV-40s (71 percent) offer significant additional reductions, although short of the possible reductions from HFCVs calculated by the hydrogen study committee (80 percent) (Section D.10).

D.12 ENVIRONMENTAL ASSESSMENT OF PLUG-IN HYBRID ELECTRIC VEHICLES, VOLUME 1 (EPRI AND NRDC, 2007)

EPRI and the NRDC examined the potential for GHG reductions due to the widespread adoption of PHEVs. The study looked at the timeframe of 2010 (when they assumed PHEVs would first hit the market) to 2050.

D.12.1 Power Generation

PHEVs can be thought of as a dual-fuel vehicle—any reduction in GHG emissions relative to a normal hybrid will have to come as a function of use of the secondary fuel (electricity) and its carbon intensity. Therefore, this study first examined the carbon intensity of the grid from 2010-2050 using EIA's National Energy Modeling System and EPRI's own National Electric System Simulation Integrated Evaluator.

Three scenarios were considered—a low-, medium-, and high-CO_2 scenario—each representing a different projection of the electrical grid of the future. In the high-CO_2 scenario, there is not a significant adoption of renewable and other low-GHG-emitting power generation sources. Furthermore, there is no economic incentive (such as cap-and-trade or a carbon tax) for producers to de-carbonize power production. In this case, total GHG emissions from the grid increase by 25 percent by 2050. In the medium-CO_2 scenario, there is a moderate cost of carbon that helps push adoption of low-CO_2 energy sources as well as greater technological advancement allowing for biomass plants and CCS on new plants. This results in a decrease in total GHG emission by 41 percent between 2010 and 2050. Finally, the low-CO_2 scenario represents the greatest adoption of low-CO_2 energy sources as well as the most advanced technology, allowing for retrofits of "dirty" coal plants with CCS and greater efficiencies of renewable energy sources. This results in a net decrease in GHG emissions from power generation of 85 percent. The assumptions leading to these scenarios are given in Table D.13.

TABLE D.13 Key Parameters of Power Generation Scenarios

Scenario Definition	High CO_2 Intensity	Medium CO_2 Intensity	Low CO_2 Intensity
Price of greenhouse gas emission allowances	Low	Moderate	High
Power plant retirements	Slower	Normal	Faster
New generation technologies	Unavailable: Coal with CCS New nuclear New biomass	Available: IGCC coal with CCS New nuclear New biomass Advanced renewables	Available: Retrofit of CCS to existing IGCC and PC plants
	Lower performance: SCPC, CCNG, GT, wind, and solar	Nominal EPRI Performance Assumptions	Higher performance: Wind and solar
Annual electricity demand growth	1.56% per year on average	1.56% per year on average	2010-2025: 0.45% 2025-2050: None

NOTE: PC = pulverized coal; CCNG = combined cycle natural gas; CCS = carbon capture and storage; SCPC = supercritical pulverized coal; GT = gas turbine (natural gas).

TABLE D.14 Peak New Vehicle Market Share in 2050 for the Three PHEV Adoption Scenarios

2050 New Vehicle Market Share by Scenario		Vehicle Type		
		Conventional	Hybrid	Plug-In Hybrid
PHEV Fleet Penetration Scenario	Low PHEV Fleet Penetration	56%	24%	20%
	Medium PHEV Fleet Penetration	14%	24%	62%
	High PHEV Fleet Penetration	5%	15%	80%
Baseline Fleet Penetration Scenario	Low PHEV Fleet Penetration	70%	30%	0%
	Medium PHEV Fleet Penetration	37%	63%	0%
	High PHEV Fleet Penetration	25%	75%	0%

D.12.2 Market Penetration

EPRI and NRDC determined that PHEVs would be applicable not just in the light-duty gasoline and diesel vehicle sector but also to heavy-duty vehicles up to 19,500 pounds (Class 5). Three different scenarios for PHEV penetration into these sectors by 2050 were considered (Table D.14). The penetration scenario is characterized by the familiar S-shape, with the majority of adoption occurring by 2020. It is also assumed that the share of PHEV-20s and PHEV-40s within the PHEV class will grow over time. The baseline case represents what the scenario would look like in the absence of PHEVs, yielding the same ratio of HEVs to conventional vehicles as in the PHEV penetration scenario.

D.12.3 Results

Figure D.16 shows the relative GHG emissions for conventional, hybrid electric, and PHEVs with a 20-mile all-electric range (PHEV-20). Included in the PHEV values are the upstream emissions from different types of power plants. This graph shows the significance of the carbon intensity of the grid itself on the effectiveness of the PHEV at reducing GHG emissions. Figure D.16 shows the values in 2050 given the deployment of advanced low-CO_2 power generators. These values also incorporate increases in fuel economy in conventional and hybrid vehicles.[3]

Table D.15 shows the annual CO_2 reduction from PHEVs in 2050 in each of the nine scenarios. Even in the highest carbon grid case, they find significant potential for GHG reductions with a net market penetration of 20 percent. The cumulative CO_2 reductions amount to between 3.4 and 10.3 billion tons of carbon between 2010 and 2050.

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[3] When the PHEV is running in charge-sustaining mode, it is assumed that it will have the same fuel economy as a hybrid vehicle. The hybrid is assumed to have 35 percent better fuel consumption than a similar conventional vehicle. Fuel consumption is projected to improve for all vehicles at a rate of 0.5 percent per year.

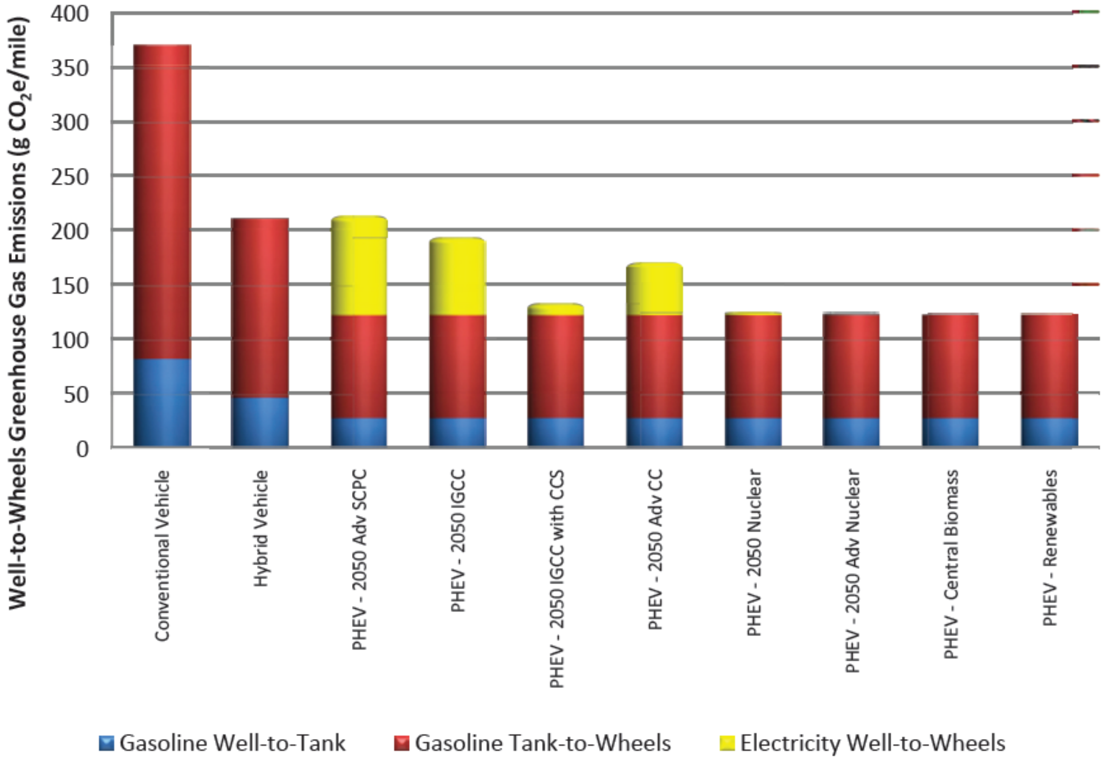

FIGURE D.16 Year 2050 comparison of greenhouse gas emissions from a light-duty, gasoline-power PHEV-20 when charged entirely with electricity from specific power plant technologies (assuming 12,000 miles driven per year).

TABLE D.15 Annual CO_2 Reductions in 2050 for the Nine Analyzed Scenarios

2050 Annual CO_2 Reductions (million tons)		Electric Sector CO_2 Intensity		
		High	Medium	Low
PHEV Fleet Penetration Scenario	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

D.13 STRATEGIES FOR REDUCING THE IMPACT OF SURFACE TRANSPORTATION ON GLOBAL CLIMATE CHANGE (BURBANK, 2009)

This study was commissioned by the American Association of State Highway and Transportation Officials as part of the National Cooperative Highway Research Program through the TRB and examines the ability of the United States to reduce GHG emissions in the transportation sector. A significant reduction in transportation GHGs (70 percent below 2005 levels by 2050) was analyzed in this study based on state-adopted and federally proposed targets for total GHG emissions reductions. In order to meet this level, the authors focused on four potential areas of reduction: (1) vehicle technologies, (2) alternative fuels, (3) VMT, and (4) vehicle/system operations.

TABLE D.16 Year 2050 Scenarios Evaluated; Change in Emissions Compared to 2005

Scenario Concept Description	GHG emission reduction per mile	Annual Change to VMT	Operational Efficiency Improvements by 2050	2050 GHG % Change compared to 2005 Baseline
Baseline forecast from DOE AEO 2008	41%	+1.74%	None	+11%
“Stretch” fleet GHG efficiency and 1% VMT	79%	+1.0%	10%	−76%
AASHTO approximated scenario with more aggressive operational efficiency improvements	72%	+1.0%	15%	−69%
AASHTO approximated scenario with improved operational efficiency improvements	72%	+1.0%	10%	−64%
Improved fleet GHG efficiency; near-zero VMT per capita increase	72%	+0.9%	10%	−66%
Fleet GHG efficiency; near-zero VMT per capita increase	58%	+0.9%	10%	−44%
Fleet GHG efficiency; more aggressive operational improvements; lowest VMT growth	58%	+0.5%	15%	−56%

SOURCE: Adapted from Burbank (2009), Table 3.1.

D.13.1 Light-Duty Vehicle Scenarios

In order to ascertain future directions of policy and the potential for GHG reductions in the transportation sector, a series of projected scenarios were carried out looking forward to GHG emissions in 2050. They assumed some amount of operational efficiency improvements (e.g., traffic smoothing, “ecodriving”) in every scenario but the BAU baseline case. Each scenario offers varying levels of vehicle efficiency and VMT. Results are summarized in Table D.16.

The baseline case results in an increase in GHG emissions due to increased VMT despite a 41 percent reduction in efficiency. Only one scenario (that requiring a 100 mpgge fleet, shown in Figure D.17) was shown to meet the 70 percent GHG reduction benchmark according to the study. With significant improvements in operational efficiency, a less aggressive efficiency mark (75 mpgge, just slightly lower than the study’s estimated efficiencies for available fuel cell and PHEVs) would nearly meet this 70 percent target as well.

D.13.2 Medium- and Heavy-Duty Vehicle Scenarios

The projected scenarios for the medium- and heavy-duty vehicles are significantly less complicated than that for the LDVs. The baseline scenario was developed first from the EIA’s Annual Energy Outlook (AEO) from 2008, which showed an annual increase in VMT for medium- and heavy-duty trucks of about 1.68 percent. The average annual increase in energy consumption by the fleet in the EIA AEO 2008 from 2005 to 2030 was then extrapolated out to 2050. The energy consumption was converted to GHG emissions using the fuel mix for the fleet. The baseline case does include proposed fuel economy standards from the EISA 2007 and the Renewable Fuel Standard. The percentage of fuels by fuel type from 2031 to 2050 was assumed to be the same as percentages of fuel by fuel type in 2030.

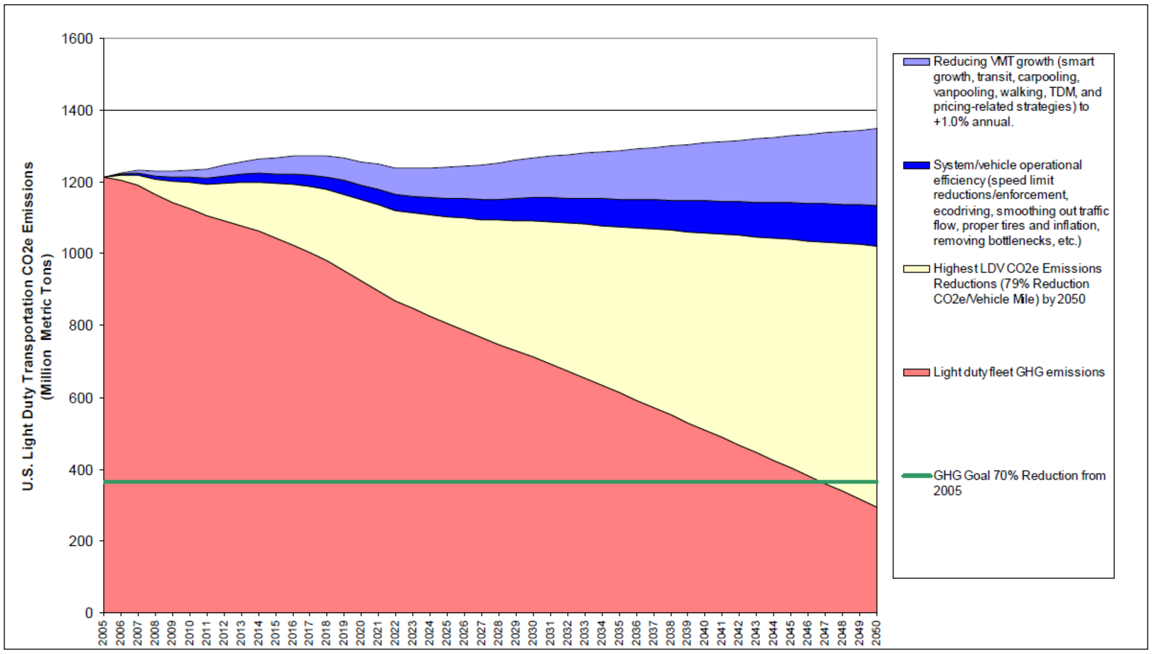

FIGURE D.17 Scenario 1—1 percent vehicle miles travelled (VMT) growth, 100 mpgge LDV fleet in 2050, improving operational efficiency.

A second scenario was projected that saw marked fuel efficiency improvements in the medium- and heavy-duty fleet. These improvements are based on the 21st Century Truck Program, which includes the development and demonstration of heavy-duty hybrid propulsion technology. A rapid fleetwide transition to this technology is assumed by 2030; this trend was projected out to 2050, resulting in a net efficiency improvement of 133 percent. However, even with these efficiency gains, the net GHG emissions for the medium- and heavy-duty fleet are barely sufficient to counter the increase in GHG emissions due to increasing VMT (Figure D.18).

D.14 ASSESSMENT OF FUEL ECONOMY TECHNOLOGIES FOR LIGHT-DUTY VEHICLES (NRC, 2011)

The Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy was faced with the task of assessing the costs of LDV technologies that might be used to reduce fuel consumption in vehicles over the next 15 years, including significant changes to the powertrain and advanced lightweighting. Homogeneous-Charge Compression Ignition (HCCI) engines are a technology that has been perennially 10 years on the horizon, and it was deemed by the committee to be beyond the 15-year scope of the study. Advanced diesel is available today in the United States, but the committee felt that much of the fuel consumption benefit will be offset by fuel consumption increases in the future (2014-2020) to meet more stringent emissions standards. While there are fully electric battery-powered vehicles in the marketplace today, the committee found that the most likely electrification scenario over the next 15 years would be for range-extended electric vehicles to make major inroads due to high battery costs forcing a limited range and/or extremely high costs for BEVs without breakthrough technology. While the committee noted that every major original equipment manufacturer (OEM) has a fuel cell vehicle program, through interviews and presentations they found little evidence that a commercially viable fuel cell vehicle will be available in significant numbers by 2020. Furthermore, the difficulty of providing the hydrogen infrastructure necessary to support HFCVs and other factors suggested to the committee that there would not be wide use of fuel cell vehicles before 2025. Finally, in regards to

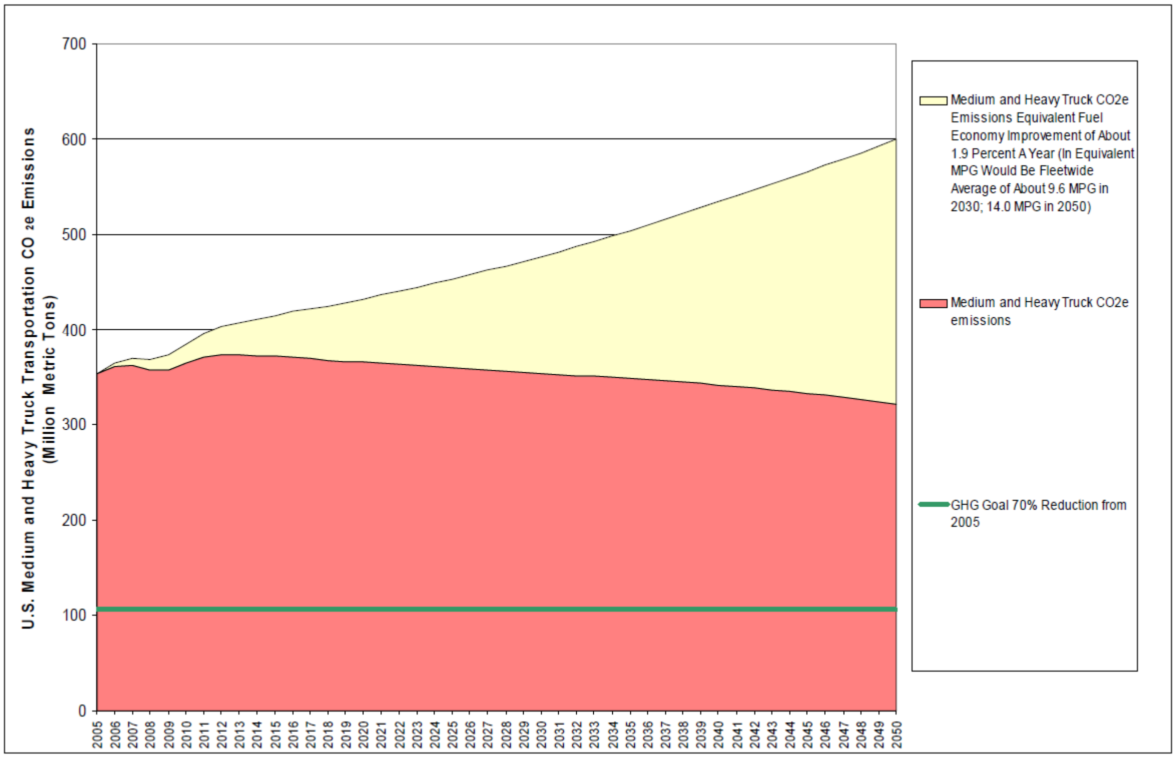

FIGURE D.18 Truck Fleet Efficiency Improvement Scenario: Annual VMT of 1.68 percent and 14 mpgge in 2050.

lightweighting, while the committee made no long-term projection of how light a vehicle could get, they noted that achieving a mass reduction of 10-20 percent will require a significant change in vehicle design, which will in turn increase costs. The uncertainty and instability of commodity prices (e.g., for aluminum or carbon fiber compared to steel) also increase the risk to OEMs of adopting these new materials.

D.15 LIGHT-DUTY VEHICLE FUEL CONSUMPTION DISPLACEMENT POTENTIAL UP TO 2045 (ANL, 2011)

The Vehicle Modeling and Simulation group at Argonne National Laboratory prepared a report that examined the technologies likely to be implemented by 2045 and the costs associated with them in order to evaluate the breadth of LDV technologies and ensure that the DOE is focusing its research on the most promising technologies. In order to simulate the uptake of the technologies, the researchers modeled vehicles packaged using various vehicle technologies. In all, more than 2,000 different vehicles were simulated. These different vehicles were chosen to simulate the various combinations of powertrain (i.e., power-split hybrid, conventional, full-electric) and fuel (i.e., gasoline, E85, diesel) available for each of the five vehicle classes (compact and midsize cars, small and large SUVs, and pick-up trucks).

Among its key findings, the report concludes that significant weight reductions (up to 37 percent in the most optimistic scenario) can be achieved by 2045, compared to current state of the art, especially for vehicles with large batteries and/or using hydrogen fuel. Owing to this, the peak power of engines/motors can be reduced significantly over time while maintaining current vehicle technical specifications.

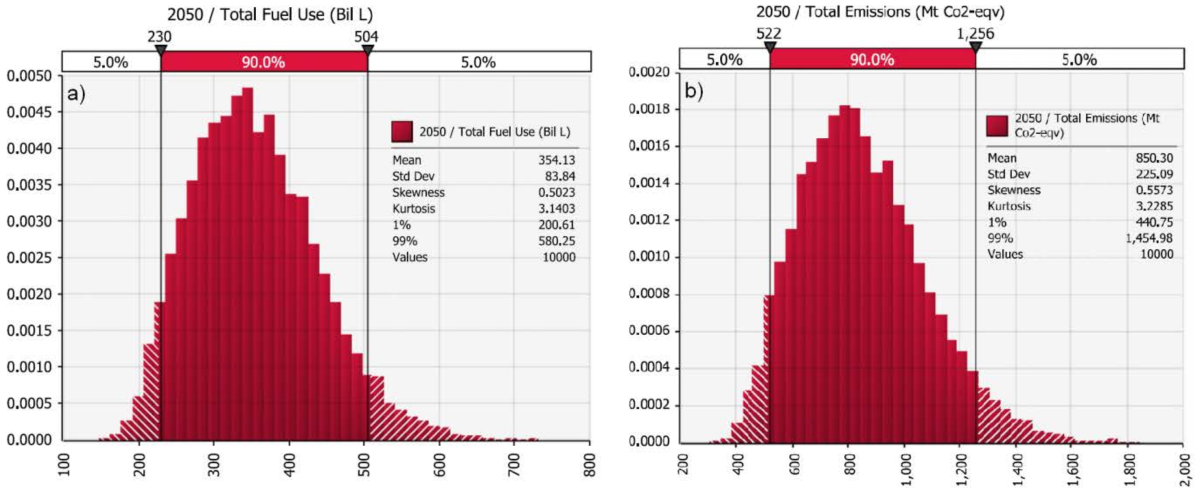

FIGURE D.19 Simulated total fuel use (a) and GHG emissions (b) for the US LDV fleet in 2050.

The most prominent conclusion is that due to expected improvements, this report finds that advanced technologies are expected to have significant market penetration. In the short term (to 2015), HEVs and PHEVs offer significant fuel displacement with an acceptable additional cost; however, BEVs are likely to remain expensive and range-limited, hindering their initial market penetration. In the medium term (to 2030), hybridized hydrogen-fueled ICE-powered vehicles would offer significant fuel improvements and could potentially act as a bridging technology to establish the infrastructure required for fuel cell vehicles. In the long term (to 2045), fuel cell vehicles demonstrate the highest fuel displacement potential at a competitive cost.

D.16 THE EFFECT OF UNCERTAINTY ON U.S. TRANSPORT-RELATED GHG EMISSIONS AND FUEL CONSUMPTION OUT TO 2050 (BASTANI ET AL., 2012)

Bastani, Heywood, and Hope employed a deterministic model to shed light on the likely future of LDVs in 2050. The scenarios given by the model are based around the statistical uncertainty of key parameters driving future deployment, such as vehicle technology performance, fuel performance and GHG emissions, alternative fuel availability, and demand and market deployment of new technologies and fuels. Tens of thousands of "futures" are considered via Monte Carlo simulation using parameter values obtained via a thorough review of the literature.

Figure D.19 shows simulated fuel use and GHG emissions for the simulated scenarios. While these values are meant to represent *likely* scenarios for future LDV pathways, which is inconsistent with the committee's task, they do show both the high potential for significant reductions in oil use and GHG emissions from efficiency improvements as well the high degree of uncertainty in any such modeling endeavor.

Figure D.20 outlines the most significant parameters affecting the future GHG emissions of the light duty fleet, according to the statistically modeled scenarios. The most significant contribution is the uncertainty in future vehicle sales, as should be obvious since the number of vehicles is directly proportional to the GHG emissions of the fleet. This is followed by the percentage of cellulosic ethanol in future gasoline, which has a strong impact on the well-to-wheel emissions of the fleet. There is a comparable strong dependence on the emphasis on reducing fuel consumption (ERFC). The ERFC represents the relative importance of fuel consumption as engines are improved—for example, in the 1990s the ERFC was near zero, while engine improvements were devoted primarily to increasing horsepower. Because the future fleet is dominated by spark-ignited ICE vehicles, the relative fuel

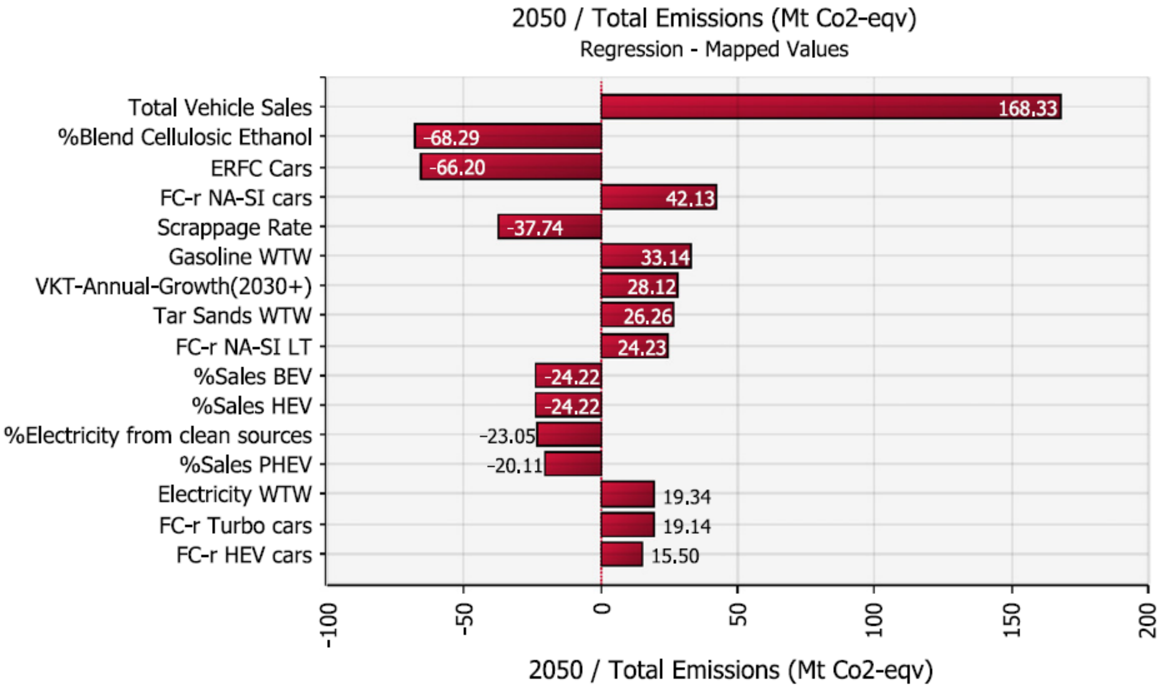

FIGURE D.20 Major influences on the simulated GHG emissions for the U.S. LDV fleet in 2050.

consumption of such vehicles is also a significant contributor. Scrappage is another strong contributor because it helps set the rate at which new technology penetrates the fleet. Because plug-in and HEVs are not expected to be a significant fraction of the fleet in this work, assumptions about their sales and the emissions from the grid are much less significant to future scenarios than VMT or well-to-wheels emissions from gasoline.

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E

Glossary, Conversion Factors, and Acronyms and Abbreviations

GLOSSARY

aerodynamic resistance	Velocity-dependent resistance from movement by a vehicle through the air. Also known as aerodynamic drag.
alcohol fuels	Fuels that are organic compounds that contain one or more hydroxyl groups (-OH) attached to one or more of the carbon atoms in a hydrocarbon chain. Common alcohol fuels include ethanol, methanol, and butanol.
algae	A group of aquatic eukaryotic organisms that contain chlorophyll. Algae can be microscopic in size (microalgae) or observable to the eye (macroalgae).
aliphatic alcohol	An alcohol that contains a hydrocarbon fragment derived from a fully saturated, nonaromatic hydrocarbon.
anoxia	Condition characterized by the absence of dissolved oxygen.
biodiesel	Diesel fuel consisting of long-chain alkyl esters derived from biological material such as vegetable oils, animal fats, and algal oils.
biofuel	Fuel derived from biomass.
biomass	Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal residues, municipal residues, and other residue materials.
biorefinery	A commercial-scale processing facility that successfully integrates all processes for extracting and converting biomass feedstocks into a spectrum of saleable products.
body in white (BIW)	The stage in vehicle manufacture when all the fixed sheet metal components are fastened together. It does not include movable parts such as doors, hood, and trunk (these are considered closures).
carbon sequestration	Net transfer of atmospheric carbon dioxide into long-lived carbon storage.
cellulose	A polymer of glucose, $(C_6H_{10}O_5)n$, that forms the cell walls of most plants.
charge-depleting (CD) mode	Electric vehicles powered by their batteries which are discharging.
charge-sustaining (CS) mode	Operation of a PHEV on its engine because the battery is discharged.

drivetrain	The power source (an engine or motor) and the components of the vehicle used to transmit this power to the wheels (transmission, drive shaft, etc.). Also called powertrain.
drop-in fuel	A non-petroleum fuel that is compatible with existing infrastructure for petroleum-based fuels with little to no modification required of current ICE vehicles.
engine heat recovery	About one-third of fuel energy is rejected as heat in the exhaust. Some of this energy can be recovered through mechanical or electric turbines (turbocompounding) or thermoelectric conversion and used to improve the efficiency of the vehicle.
ethanol	Best known as the type of alcohol found in alcoholic beverages, ethanol can be used both as a fuel additive (in mixtures with gasoline, as in the E10 standard) and as a liquid fuel itself.
exhaust gas recirculation (EGR)	EGR recirculates cooled exhaust gas back through the engine to reduce throttling losses and allow operation over a wider range of load and speed.
gasoline direct injection (GDI)	Gasoline is directly injected into the combustion chamber of the engine, providing better fuel vaporization and more stable combustion. GDI reduces fuel consumption across the range of engine operations.
greenhouse gas (GHG)	An atmospheric gas that absorbs and emits radiation in the infrared range. Common GHGs are CO_2, NO_x, CH_4, and ozone (O_3).
hemicellulose	A matrix of polysaccharides present in almost all plant cell walls with cellulose.
Highway Fuel Economy Test (HWFET)	A component of the federal test procedure that simulates free-flowing highway driving.
hybrid electric vehicle (HEV)	A vehicle combining a fuel-driven engine, electric motor(s), and a battery or ultracapacitor. It is designed to reduce fuel consumption primarily by turning off the engine during idle, braking, and coasting as well as by capturing braking energy using regenerative brakes. Types of hybrid vehicles include micro- or stop/start hybrids, P2 hybrids, and power-split hybrids.
hydrocarbon fuels	Fuels that are organic compounds containing primarily carbon and hydrogen and only minor amounts of other atoms such as sulfur, nitrogen, and oxygen. Most hydrocarbon fuels are derived from petroleum.
hypoxia	Low dissolved oxygen concentrations, generally less than 2 milligrams per liter.
internal combustion engine (ICE)	An engine in which the combustion of a fuel (most often gasoline or diesel) drives a piston, producing useful mechanical energy.
land cover	Plants or physical cover over the surface of land.
land use	Anthropogenic activities, such as agriculture, forestry, and urban development, that alter land-surface processes, including biogeochemistry, hydrology, and biodiversity.

lignin	A complex polymer that occurs in certain plant cell walls. Lignin binds to cellulose fibers and hardens and strengthens the cell walls of plants.
lignocellulosic biomass	Plant biomass composed of cellulose, hemicellulose, and lignin.
multi-material vehicle (MMV)	A vehicle made primarily of lightweight components, including high-strength steel, aluminum, magnesium, and carbon fiber.
pilot demonstration	A small, pre-commercial facility intended to test the viability of a process. These facilities typically do not include fully integrated processes. A pilot demonstration of a biofuel refinery might process 1-10 dry tons of feedstock per day.
plug-in electric vehicle (PEV)	A vehicle propelled (at least in part) by an electric motor that draws its power from a battery that stores energy from the electric grid. This includes both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).
powertrain	See drivetrain.
pumping loss	The energy that must be expended in delivering air into an ICE.
retail price equivalent (RPE)	A multiplier applied to the manufacturing cost of a component to account for indirect costs of manufacturing, meant to represent the fraction of the retail price of the fully assembled product associated with the component.
rolling resistance	The resistance to vehicle movement due to friction in the tires and from the road. It is directly proportional to the mass of the vehicle and depends on tire design (shape, tread, materials) and inflation pressure.
tractive energy	Energy delivered by the drivetrain to a vehicle’s wheels.
turbocharging	A process in which exhaust gas drives a turbine that compresses the air entering the engine cylinders, increasing the amount of fuel that can be burned in the cylinders and thus increasing torque and power output.
Urban Dynamometer Driving Schedule (UDDS)	A component of the federal test procedure that simulates stop-and-go driving.
US06 Supplemental Federal Test Procedure (SFTP)	A driving schedule test that simulates high speeds as well as hard acceleration and braking.

CONVERSION FACTORS

Mass

1 ounce (oz) ≡ 28.3495231 g
1 pound ≡ 0.453592 kg
1 (short) ton ≡ 0.907185 (metric) tonne

Length

1 ft (foot) ≡ 0.3048 m (meter)
1 mile ≡ 1.609344 km (kilometer)

Area

1 mi^2 ≡ 2.589988 km^2
1 acre ≡ 0.404685642 hectare (ha)

Volume

1 ft^3 ≡ 0.028317 m^3
1 gallon ≡ 3.785412 liter (L)
1 barrel ≡ 158.987295 L

Energy

1 British thermal unit (Btu) ≡ 0.001055 megajoule (MJ)

Pressure

1 pound per square inch (psi) ≡ 6,894.76 Pascal (Pa)

Compound units

1 pound per bushel ≡ 17.857143 kg/tonne
1 pound per acre ≡ 1.120851 kg/ha
1 bushel per acre ≡ 0.062768 tonne/ha
1 ton per acre ≡ 2.241702 tonne/ha
1 ounce (oz) per gallon ≡ 7.489152 g/L
1 ounce per Btu ≡ 26,870.16 g/MJ
1 ft^3/acre ≡ 0.028317 m^3/ac
1 ft^3/Btu ≡ 26,839.19 m^3/GJ
1 Btu per gallon ≡ 0.000279 MJ/L

ACRONYMS AND ABREVIATIONS

ABO	Algal Biomass Organization
AC	alternating current
AEF	*America's Energy Future*
AEO	*Annual Energy Outlook*
AER	all-electric range
AFV	alternative fuel vehicle
Ah	ampere-hour
AMT	automatic conventional manual transmission
ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
ATR	autothermal reforming
BAU	business as usual
bbl	barrel
BD	biodiesel
BDT	bone dry ton
BEV	battery electric vehicle
BGY	billions of gallons per year
BIW	body in white
BLM	Bureau of Land Management
BLY	billion(s) of liters per year
BM	biomass
BMEP	brake mean effective pressure
BMS	battery management system
BOP	balance of plant
Btu	British thermal unit
CAA	Clean Air Act
CAFE	Corporate Average Fuel Economy
CARB	California Air Resource Board
CBO	Congressional Budget Office
CBTL	coal-and-biomass to liquid fuel
CCS	carbon capture and storage
CD	charge depleting
CFRC	carbon-fiber reinforced composite

CH_4	methane
CI	carbon intensity
CID	current interrupt device
cm	centimeter
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CS	charge sustaining
CSBP	Council on Sustainable Biomass Production
CTL	coal to liquid (fuel)
DAF	dissolved air flotation
DC	direct current
DCT	dual-clutch transmission
DGAT	diacylglycerol acyltransferase
DME	dimethyl ether
DNA	deoxyribonucleic acid
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DW	dry weight
E10	blend of up to 10 percent ethanol and the balance petroleum-based gasoline
E15	fuel containing up to 15 percent ethanol by volume
E85	fuel containing up to 85 percent ethanol by volume
EEA	European Environmental Agency
EER	energy economy ratio
EERE	Office of Energy Efficiency and Renewable Energy
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EIOLCA	economic input-output approach to LCA
EISA	Energy Independence and Security Act of 2007
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
EPCA	Energy Policy and Conservation Act

EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
EROI	energy return on investment
EROWI	energy return on water invested
ESA	Ecological Society of America
ETA	Energy Tax Act
EU	European Union
EV	electric vehicle
FAME	fatty acid methyl ester
FAO	Food and Agriculture Organization of the United Nations
FCEV	fuel cell electric vehicle
FFV	flex-fuel vehicle
FHWA	Federal Highway Administration
F_{in}	make up water addition
F_{out}	water purge
FT	Fischer-Tropsch
FTP	federal test procedure
GBEP	Global Bioenergy Partnership
GD	green diesel
GDI	gasoline direct injection
gge	gallon of gasoline equivalent
GGT	gas guzzler tax
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GTI	Gas Technology Institute
GTL	gas to liquid (fuel)
GW	gigawatt
ha	hectare
H_2	hydrogen
HD	heavy-duty; horizontal drilling
HEV	hybrid electric vehicle
HF	hydraulic fracturing
HRAP	high rate algal pond
HVAC	heating, ventilation, and air conditioning

HWFET	Highway Fuel Economy Test
IANGV	International Association for Natural Gas Vehicles
IBR	Integrated Algal Biorefinery
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IHUF	Indexed Highway User Fee
IISD	International Institute for Sustainable Development
ILUC	indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
IPM	interior permanent magnet
ISO	International Organization for Standardization
ISSG	Invasive Species Specialist Group
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
LCA	life-cycle assessment
LCFS	Low Carbon Fuel Standard
LDV	light-duty vehicle
Li-ion	lithium ion
LLNL	Lawrence Livermore National Laboratory
LNG	liquid natural gas
LT	light truck
LUC	land use change
MD	medium-duty
MEA	Millennium Ecosystem Assessment
MIT	Massachusetts Institute of Technology
MMBPD	million barrels per day
$MMTCO_2e$	million metric ton(s) of CO_2 equivalent
MPa	mega-Pascal
mpg	miles per gallon
mpgge	miles per gallon of gasoline equivalent
mt	metric ton (or tonne)
MTBE	methyl tertiary-butyl ether

MTG	methanol-to-gasoline (process)
MY	model year
NAAQS	National Ambient Air Quality Standards
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NBB	National Biodiesel Board
NEMS	National Energy Modeling System
NER	net energy ratio
NETL	National Energy Technology Laboratory
NEV	net energy value
NG	natural gas
NGV	natural gas vehicle
NHTSA	National Highway Traffic Safety Administration
Ni-MH	nickel metal-hydride
NIST	National Institute of Standards and Technology
NLTS	nineteen lower-tier state region
NMC	nickel-manganese-cobalt oxide
NO_x	mono-nitrogen oxides, including nitric oxide (NO) and nitrogen dioxide (NO_2)
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
OBP	Office of Biomass Program
OEM	original equipment manufacturer
OMEGA	Offshore Membrane Enclosure for Growing Algae
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTAG	Ozone Transport Assessment Group
PAYD	pay as you drive
PBR	photobioreactor
PEM	proton-exchange membrane
PEV	plug-in electric vehicle
PG&E	Pacific Gas and Electric
PHEV	plug-in hybrid electric vehicle

PHEV##	plug-in hybrid electric vehicle with an all-electric range of ## miles
PL	public law
PM	permanent magnet
PMC	polymer-matrix composite
PNGV	Partnership for a New Generation of Vehicles
psi	pounds per square inch
PTC	positive temperature coefficient
PZEV	partial zero emission vehicle
quad	quadrillion British thermal units (of energy)
R&D	research and development
RD3	research, development, demonstration, and deployment
RFS	Renewable Fuel Standard
RFS2	Renewable Fuel Standard, as amended by EISA
RIA	regulatory impact analysis
RIN	Renewable Identification Number
RNA	ribonucleic acid
RNG	renewable natural gas
RPE	retail price equivalent
RSB	Roundtable on Sustainable Biofuels
RSO	rapeseed oil
SBO	soybean oil
SCE	Southern California Edison
scf	standard cubic feet
SE	Southeast
SOC	state of charge
SPM	surface-mounted permanent magnet
SR	switched reluctance
SUV	sport utility vehicle
SVR	surface-to-volume ratio
SW	Southwest
TAGs	triacylglycerol
TAR	technical assessment report
TCC	thermochemical conversion
tcf	trillion(s) of standard cubic feet

TEPCO	Tokyo Electric Power Company
TOU	time of use
TSCA	Toxic Substances Control Act
TTW	tank to wheel
UDDS	Urban Dynamometer Driving Schedule
USCAP	U.S. Climate Action Partnership
USDA-RD	U.S. Department of Agriculture Rural Development
USGS	United States Geological Survey
VEETC	volumetric ethanol excise tax credit
VMT	vehicle miles traveled
VOC	volatile organic compound
W	watt
WF	water footprint
Wh	watt-hour
WHC	Wildlife Habitat Council
WTT	well to tank
WTW	well to wheels
WW	wastewater
WWTP	wastewater treatment plant
$x_{control}$	total dissolved solids in water (defined control point)
x_{out}	total dissolved solids in purge
ZEV	zero-emission vehicle

F

Vehicles

This appendix is an addendum to Chapter 2 of the main report, providing additional information on subjects discussed there. Section F.1 discusses efficiency technologies for internal combustion engine (ICE) vehicles (ICEVs) and hybrid electric vehicles (HEVs). Some of these technologies also apply to other types of vehicles. Section F.2 discusses the modeling techniques uses to estimate future fuel consumption. Two spreadsheet models are also included in the electronic version of this appendix. The Vehicle Input Spreadsheet shows the committee's estimates of the reduction in energy losses over time for the six vehicles analyzed. The Vehicle Cost Summary estimates the cost of the various vehicles analyzed (6 models each of ICEVs, HEVs, battery-powered electric vehicles [BEVs], and hydrogen fuel cell electric vehicle [FCEVs]). Section F.3 elaborates on the battery vehicle section of Chapter 2, and Section F.4 on the hydrogen fuel cell electric vehicle section.

F.1 EFFICIENCY TECHNOLOGIES FOR CONVENTIONAL VEHICLES

F.1.1 Load Reduction Technologies Applicable to All Vehicles

F.1.1.1 Mass Reduction

This discussion is focused on the potential benefits of reducing the mass of vehicles to improve fuel economy. The government's fuel economy standards are footprint based and provide no incentive for downsizing vehicles. Potential effects on safety, fuel economy, and vehicle costs are discussed for scenarios where mass reduction is accomplished entirely through material substitution and smart design that can reduce mass without changing a vehicle's functionality or safety performance and maintains structural strength.

Fuel Economy Benefits

The engineering rule of thumb, assuming appropriate engine resizing is applied and vehicle performance is held constant, is that a 10 percent curb weight reduction results in a 6-7 percent fuel consumption savings (NHTSA-EPA, 2010). For this committee's analysis, the fuel consumption from weight reduction is calculated as one of the inputs into an energy audit model.

Potential for Mass Reduction

The National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) examined mass reductions of 15-30 percent for the 2017-2025 timeframe (NHTSA-EPA, 2010). The automobile manufacturers' position, as characterized in the Technical Assessment Report (TAR), was that mass reduction plans for 2017-2025 were focused on increased use of high strength steel and some additional aluminum with resulting mass reductions of 10-15 percent. Manufacturers generally indicated that universal material substitution (such as a switch from steel to aluminum body in white (BIW)[1] structures) would not be feasible across all body lines in the 2017-2025 timeframe. In the TAR covering 2017-2025 Model Years, the government stated that "the ability of the industry to reduce mass beyond 20% while maintaining vehicle size . . . is an open technical issue" (EPA-NHTSA-CARB, 2010, p. 3-8).

The Partnership for New Generation Vehicles research effort from 1994-2002 was an early effort to conceptualize and build highly fuel efficient vehicles. The mass reduction goal was 40 percent. Actual vehicles achieved a mass reduction of 20 to 30 percent (NRC, 2001).

A recent study by the University of Aachen, done for the European Aluminum Association, looked at weight reduction opportunities for aluminum versus steel for subcompact and medium-sized passenger vehicles, crossover vehicles, and small multi-purpose vehicles. The Aachen study looked at optimizing the BIW and closures with aluminum intensive designs and concluded that a 40 percent weight savings in these areas was possible. BIW and Closure Reductions of 40-45 percent translate to an incremental (taking into account aluminum content already in standard production vehicles) 10-11 percent total vehicle weight reduction and with secondary weight savings yield approximately a 15 percent reduction in total vehicle weight (Aachen, 2010).

The 15 percent weight reduction of the total vehicle was repeated in detailed design studies by IBIS Associates, Inc., although secondary weight savings and use of lightweight materials in the rest of the body would result in much greater overall weight savings (IBIS, 2008). An interesting aspect of the Aachen study is that it looked specifically at the use of the aluminum-intensive parts from the standpoint of vehicle stiffness (handling, comfort, noise) and strength needed for managing crash energies and constrained the proposed design to meet or exceed current vehicle BIW performance when it quantified weight reduction opportunities.

Lotus showed similar conclusions to the Aachen study regarding BIW weight savings (Lotus, 2010). The Lotus study evaluated the total vehicle design and hypothesized a "high development" vehicle using an aluminum/magnesium intensive design with an overall weight reduction of about 40 percent. The primary areas of mass reduction are:

- Body in white and closures—44 percent,
- Interior—20 percent, and
- Suspension/chassis—33 percent.

The aluminum industry sponsored studies, which looked strictly at weight reduction for the BIW and closures with associated secondary weight reduction, are in agreement with the Lotus study for similar areas of the vehicle. Lotus also used increased aluminum as part of the suspension and chassis optimized design.

Polymer-matrix composites (PMC, e.g., carbon fiber) have the potential to make a significant further contribution to reducing mass if the production costs of such materials can be reduced with mass production. "Conservative estimates are that carbon fiber PMC can reduce the mass of a steel structure by 40-50 percent . . ." (NRC, 2011, p. 102). However, there are currently production concerns for using carbon fiber in mass-produced vehicles. Currently, there still is not a known substitute for the existing carbon fiber process, which is too expensive for high-volume applications. Because of this uncertainty, the committee has not included carbon fiber in the 2050 mass reduction scenarios.

A key factor when evaluating design strategies for reducing mass is the corresponding secondary weight savings from rationalizing chassis, suspension, and drivetrain performance for the reduced mass. Estimates of the synergistic effects of mass reduction and the compounding effect that occurs along with it can vary significantly. In comments to various U.S. Corporate Average Fuel Economy (CAFE) rulemaking proposals, the Auto-Steel Partnership estimates that these secondary mass changes can save

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[1] *Body in white* is the term for the stage in vehicle manufacture when all the fixed sheet metal components are fastened together. It does not include moveable parts such as doors, hood, and trunk (closures).

an additional 0.7 to 1.8 times the initial mass change. Comments by the Aluminum Transportation Group have estimated a factor of 64 percent for secondary mass reduction (NHTSA, 2010). The 2011 National Research Council (NRC) report *Assessment of Fuel Economy Technologies for Light-Duty Vehicles* pointed out the importance of secondary weight reduction "as the mass of a vehicle is reduced . . . other components of the vehicle can be reduced . . . for example brakes, fuel system, powertrain, and even crash management structures" (NRC, 2011, p. 113). It discussed a rule of thumb that for every pound saved in the design through material substitution or structural modifications, an additional 30 percent of the weight savings in secondary systems could be saved (NRC, 2011).

Potential Cost Impacts

Cost estimates for reducing vehicle mass have varied significantly. One difference is the cost savings from secondary weight reduction which can offset some of the costs related to lightweight materials and improved structural design. In this context, the net costs for mass reduction should include the secondary weight and drivetrain downsizing that are directly related to mass efficient vehicle designs. The impacts of weight reduction on drivetrain costs are discussed below.

NHTSA and EPA summarized three studies, which were first used in the 2012-2016 CAFE rulemaking, that concluded that weight could be reduced for approximately $1.50 per pound. Additionally, Sierra Research estimated a 10 percent reduction, with secondary weight reduction, could be accomplished for $1.01 per pound. The Massachusetts Institute of Technology (MIT) estimated that the weight of a vehicle could be reduced by 14 percent with no secondary weight reduction, for a cost of $1.36 per pound. The final NHTSA/EPA cost estimate for the 2012-2016 rulemaking was $1.32 per pound and was based on the average of the three referenced studies (NHTSA/EPA, 2010).

The 15 percent reduction in total vehicle weight estimated by IBIS for the Aluminum Transportation Group discussed above was estimated to cost $0.18 per pound. This cost was significantly less than the $1.32 per pound used in NHTSA/EPA's rulemaking analysis—an estimate that did not account for secondary weight savings.

Downweighting is even more cost-effective for battery-powered vehicles (or other high-cost propulsion systems) because of the potential savings in battery/energy storage. The Aachen and IBIS reports produced detailed designs using aluminum intensive BIW and Closures with weight savings of 19 percent of total vehicle weight. The increased cost of aluminum was estimated at $630. Cost savings in the study were estimated at $450-$975 for the batteries (using $375/kWh).

The Lotus study estimated that a 21 percent mass reduction could be achieved by 2020 using high-strength steel with no cost impact. A 38 percent mass reduction could be achieved by 2020 with a moderate cost growth (e.g., a 3 percent increase in vehicle cost using aluminum, magnesium, and composites; Lotus, 2010).

For the 2017-2025 proposed rule, NHTSA and EPA updated their analysis of existing cost studies. Currently the government is proposing a formula that assumes mass reduction increases in cost as the absolute size of mass reduction increases, e.g., $4.32 × % weight reduction. Table F.1 shows the results over a range of mass reduction.

Down-weighting battery powered (or other high cost propulsion systems) vehicles is even more cost effective because of the potential savings in battery/energy storage (Ricardo, 2011).

Carbon fiber/plastics may also make a significant impact on mass reduction if costs are reduced: "Conservative estimates are that carbon fiber PMC can reduce the mass of a steel structure by 40 to 50 percent (Powers, 2000)" (NRC, 2011, p. 102). The 2011 NRC report states "that the price of carbon fiber has to fall to $5 to $7 per pound (about 50 percent) before it can be cost competitive for high-volume automobiles (Carpenter, 2008)" (NRC, 2011, p. 102). Research conducted at ORNL suggests that if a vehicle design with a weight reduction of 50 percent was achieved with a 50/50 mix of plastic resin (1.00 $/#) and carbon fiber (7.00 $/#), then an average cost for using carbon fiber/plastic would be $3 to $4 per pound at a high production volume (10 million pounds per year) (ORNL, 2008).

TABLE F.1 Cost of Mass Reduction

MassR	$/lb	Incremental $/lb
10%	$0.43	$0.43
20%	$0.86	$1.30
30%	$1.30	$2.16
40%	$1.73	$3.02

Table 2.2 in Chapter 2 summarizes the weight reductions and costs that are used in the committee's scenarios. It includes carbon fiber in 2050 for context, even though the committee considers it unlikely that costs will drop sufficiently for widespread use in vehicles. For the midrange cases, 5 percentage points of the weight reduction were countered by weight increases due to increased vehicle features in 2030, and 10 percentage points in 2050. Predicted reductions of new car weight are 18-22 percent in 2030 and 28-37 percent in 2050. For light trucks, they are 17-20 percent in 2030 and 23-33 percent in 2050.

The cost estimates in Table 2.2 do not include secondary weight reductions. In general, secondary weight reductions are free or even reduce costs, as they reduce component size. However, available estimates for secondary weight reductions generally include powertrain size reduction, in addition to chassis and suspension weight reductions. As the cost benefits of powertrain size reductions are being calculated elsewhere in the analysis and the amount of secondary weight reduction for the chassis and suspension alone is uncertain, no adjustments were made to lightweight material costs.

Safety Implications

The 2011 NRC report said the following: "Vehicle mass can be reduced without compromising size, crashworthiness, and [noise/vibration/harshness] . . ." NRC (2011, p. 100).

The NHTSA/EPA Final Rule stated that "the agencies believe that the overall effect of mass reduction in cars and LTVs may be close to zero, and may possibly be beneficial in terms of the fleet as a whole."[2] This statement was based on an analysis which looked at historical experience and tried to separate out size and weight differences and how they affect real world safety performance based on vehicle designs of the 1990s, which were not optimized with innovative designs using improved, lighter weight, stronger materials, and improved structural design (NHTSA/EPA (2010b).

NHTSA/EPA issued the proposed rule "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards" (NHTSA/EPA, 2011c), which discussed an updated statistical analysis (Kahane, 2011). NHTSA created a common, updated database for statistical analysis that consists of crash data of model years 2000-2007 vehicles in calendar years 2002-2008, as compared to the database used in prior NHTSA analyses, which was based on model years 1991-1999 vehicles in calendar years 1995-2000. The study found that decreasing weight (while maintaining footprint) generally decreased fatalities in rollovers and collisions with fixed objects for all vehicles. In the other type of crashes, weight reduction in smaller vehicles tended to increase fatalities and in larger vehicles tended to decrease fatalities. NHTSA/EPA concluded, however: "The effect of mass reduction while maintaining footprint is a complicated topic and there are open questions whether future designs will reduce the historical correlation between weight and size. It is important to note that while the updated database represents more current vehicles with technologies more representative of vehicles on the road today, they still do not fully represent what vehicles will be on the road in the 2017-2025 timeframe."[3]

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[2] NHTSA/EPA, Final Rule, Federal Register, Volume 75, Number 88, May 7, 2010, p. 25383.

[3] NHTSA/EPA, Proposed Rules, Federal Register, Volume 76, Number 231, December 1, 2011, p. 74955.

Safety is primarily a design issue. Advanced designs that emphasize dispersing crash forces and optimizing crush stroke and energy management can allow weight reduction, while maintaining or even improving safety. In a crash, occupant protection is provided by designing the vehicle structure to absorb energy in a managed way and prevent intrusion into the occupant compartment. Advanced materials such as high-strength steel, aluminum, and polymer-matrix composites (PMC) have significant advantages in terms of strength versus weight. For example, pound for pound, aluminum absorbs two times the energy in a crash compared to steel and can be up to two and a half times stronger. The high strength-to-weight ratio of advanced materials allows a vehicle to maintain, or even increase, the size and strength of critical front and back crumple zones without increasing vehicle weight and maintain a manageable deceleration profile. And, given that all light-duty vehicles (LDVs) likely will be down weighted, vehicle-to-vehicle crashes should also be mitigated. Lastly, assuming mass reduction without size reduction, vehicle handling (exacerbated by smaller wheel bases, for instance) is not an issue. In fact, lighter vehicles are more agile, helping to avoid crashes in the first place.

Several significant engineering studies on mass/safety are in progress:

- NHTSA has issued a contract proposal for an engineering down-weighting design and crash simulation analysis.
- California Air Resources Board is having Lotus look at the crash worthiness of the recent design study on down weighting. And EPA is having FEV, Inc., conduct crash simulations on a high strength steel design.
- The U.S. Department of Energy (DOE) has several research studies planned. One will be looking at the amount of mass reduction that is technically feasible. A second, more ambitious project will be an actual vehicle build of a light weighted vehicle identified as a multi-material vehicle. DOE has also asked Lawrence Berkeley National Laboratory to look at mass reduction versus safety.

F.1.1.2 Reduced Rolling Resistance

About one-third of the energy delivered by the drive-train to the wheels goes to overcoming rolling resistance. Rolling resistance, and the energy required to overcome it, is directly proportional to vehicle mass. It is calculated by multiplying the tire rolling resistance coefficient times the weight on the tire. Thus if a tire with a coefficient of 0.01 is supporting 1,000 pounds, the force resisting rolling is 10 pounds.

The tire rolling resistance coefficient depends on tire design (shape, tread design, and materials) and inflation pressure. According to a 2006 NRC study, reductions in rolling resistance can occur without adversely affecting wear and traction (NRC, 2006). This study estimated the fuel consumption reduction from a 10 percent reduction in rolling resistance at 1-2 percent. Additional savings from the reduced power requirement (at constant performance) result in a total reduction of 2-3 percent. Measured rolling resistance coefficients provided by manufacturers for commercial LDV tires in 2005 ranged from 0.00615 to 0.01328, with a mean of 0.0102. The best is 40 percent lower than the mean, equivalent to a fuel consumption reduction of 4-8 percent. Vehicle manufacturers have an incentive to provide their cars with low rolling resistance tires to maximize fuel economy during certification. The failure of owners to maintain proper tire pressures and to buy low rolling resistance replacement tires increases in-use fuel consumption.

Average future improvements by 2030 are estimated to provide 20-28 percent reduction in rolling resistance relative to 2010 for a fuel consumption reduction of 5-8 percent at a cost of $25. By 2050, rolling resistance could be reduced by 35-41 percent for a fuel consumption reduction of about 10 percent. Since tires are usually replaced several times over a vehicle’s lifetime, achieving such fuel consumption improvements may depend on ensuring that replacement tires are as efficient as the vehicle’s original tires.

F.1.1.3 Improved Aerodynamics

The fraction of the energy delivered by the drive-train to the wheels going to overcoming aerodynamic resistance depends strongly on vehicle speed. The drag resistance,

$$D = ½C_d\rho AV^2$$

where

C_d = drag coefficient
ρ = density of air
A = vehicle frontal area
V = vehicle velocity.

Unlike rolling resistance, the energy to overcome drag does not depend on vehicle mass. It does depend on the size of the vehicle as represented by the frontal area. For low-speed driving, about one-fourth of the energy delivered by the drivetrain goes to overcoming drag; for high-speed driving, one-half of the energy goes to overcoming drag.

Vehicle drag coefficients vary considerably, from 0.195 for the General Motors EV1 to 0.57 for the Hummer 2. Vehicle drag can be reduced through both passive and active design changes. The drag coefficient can be lowered by more aerodynamic vehicle shapes, smoothing the underbody, wheel covers, active cooling aperture control (radiator shutters). Active ride height reduction reduces frontal area and improves tire coverage. Narrower tires reduce frontal area.

A 10 percent reduction in drag can give a 2.5 percent reduction in fuel consumption—more at high speeds, less at low speeds. A combination of technologies can reduce drag by 17-25 percent by 2030, and 30-38 percent by 2050. Improved aerodynamics could reduce fuel consumption by about 4 percent by 2030 and 8-9 percent by 2050. These changes could be implemented at low cost.

F.1.1.4 Improved Accessory Efficiency

- *Heating, ventilation, and air conditioning*—Air conditioning accounts for about 4 percent of LDV fuel consumption (EPA-NHTSA-CARB, 2010). Since the air conditioner is not operating during vehicle certification testing, there has been little incentive for manufacturers to improve air conditioning. EPA mileage labeling, however, does include air conditioner use, and new fuel economy and greenhouse gas regulations credit improved air conditioner efficiency. Multiple technologies exist for improving the efficiency of air conditioning systems, in particular in the compressor, air handling fans, and refrigeration cycles. These are estimated to reduce air conditioning related fuel consumption by 40 percent by 2016. Better cabin thermal energy management through use of solar-reflective paints, solar-reflective glazing, and parked car ventilation is projected to reduce air conditioner-related fuel consumption by 26 percent (Rugh et al., 2007). This study estimates 2030 fuel consumption reduction for improved air conditioning and thermal load management at 2 percent.

BEVs and FCEVs do not have access to ICE waste thermal energy for heating. Heat pump technology can provide these vehicles both cooling and heating with improved efficiency.

- *Efficient lighting*—The use of light emission diodes is claimed to reduce CO_2 emissions by 9 gm/mi (Osram Sylvania, 2011). This is equivalent to a fuel consumption reduction of 2.6 percent while the lights are in use.
- *Power steering*—The traditional hydraulic pump draws power from the engine whether the vehicle is turning or not. Replacing it with an electric motor, which operates only when needed, saves 2-3 percent of fuel consumption. Some weight reduction is realized and costs are similar to hydraulic systems. Both pure electric and hydroelectric systems have been used. Systems are not yet available for the largest

vehicles, but are likely well before 2030. Electric power steering is required on vehicles with any electric drive mode.

- *Intelligent cooling system*—The use of an electric coolant pump allows speed control and optimal operation. Engine friction is reduced by facilitating engine operation at the optimum temperature. An electric radiator fan, already used in most LDVs, is part of the system. Fuel consumption reduction is about 3 percent.
- *Energy generation (vehicle specific)*—Vehicles with batteries for energy storage (HEVs, plug-in hybrid electric vehicles [PHEVs], BEVs, and FCEVs) provide an opportunity for charging from on-vehicle solar cells. The value of this technology in reducing fuel consumption depends strongly on vehicle location over a 24-hour period. With a nominal power level of 100 watts (W), a reduction of fuel consumption of 0.5 to 2.5 percent is projected, but is not considered in this study.

Overall, energy consumption by accessories is estimated to drop 21-25 percent by 2030 and 30-36 percent by 2050.

F.1.2 Internal Combustion Engine and Powertrain Efficiency Improvements

F.1.2.1 Engine Technologies

Gasoline Direct Injection Engines

Although the dominant technology used to control fuel flow in gasoline engines has been port fuel injection, engines with direct injection (DI) of fuel into the cylinders have been rapidly entering the U.S. fleet. Gasoline direct injection (GDI) systems provide better fuel vaporization, flexibility as to when the fuel is injected (including multiple injections), and more stable combustion. The rapid evaporation of the direct-injected fuel spray cools the in-cylinder air charge, reducing engine knock and allowing for higher compression ratios and higher intake pressures with reduced levels of fuel enrichment. Direct injection reduces fuel consumption across the range of engine operations, including high load conditions. Although current U.S. GDI systems are stoichiometric—the air/fuel ratio is set to provide exactly the amount of oxygen needed to combust the fuel, with no excess—future systems using spray-guided injection can deliver a stratified charge (delivering more fuel close to the spark plug) and can operate with a lean air/fuel mixture (e.g., excess air). This reduces the need to throttle the air intake, reducing pumping losses and fuel consumption. Such a system would require additional NO_x controls beyond a three-way catalyst, such as a lean NO_x trap, and would likely shift to stoichiometric operation at high load conditions.

Ricardo (2011) projects a 3 percent benefit for stoichiometric DI engine, 8-10 percent benefit for stoichiometric DI turbo engines, 8-10 percent benefit for a lean DI engine, and 20-22 percent benefit for lean DI turbo engines in the 2020-2025 timeframe.

Direct injection enables more effective turbocharging and engine downsizing. In a turbocharged engine, exhaust gases are allowed to drive a turbocharger turbine that compresses the air entering the engine cylinders. This increases the amount of fuel that can be burned in the cylinders, increasing torque and power output, and allows engine downsizing. The degree of turbocharging is enhanced by GDI because of its cooling effect on the intake charge and delay of knock.

Ricardo (2011) expects turbocharged engines in the 2020-2025 time frame to have overcome many of the issues often associated with turbocharging (e.g., minimal turbo lag and a smooth acceleration feel), with one likely solution being two-stage series sequential turbocharger systems building on systems tested by General Motors (Schmuck-Soldan et al., 2011 from Ricardo report).

Another engine/turbocharger combination, exhaust gas recirculation (EGR) DI turbo, recirculates cooled exhaust gas into the cylinder to reduce intake throttling (and pumping losses) and to manage combustion knock and exhaust temperatures (Ricardo, 2011). This engine allows operation without enrichment over a wider range of load and speed and by reducing knock still further, allows a higher compression ratio over that of a stoichiometric GDI engine, thus allowing even more downsizing. Ricardo (2011) projects a 2020-2025 benefit for this engine of 15-18 percent.

Diesel Engines

This report has not explicitly considered diesel engines. The committee considered at length whether or not to include separate calculations for diesel and gasoline engines. The current efficiency advantage of the diesel is widely known, and diesels have about 50 percent of the light duty market share in Europe, both of which argue for inclusion.

It was ultimately decided that a diesel case would not add significant value to the results of this study, primarily because the efficiency advantage of the diesel will be much smaller in the future as gasoline vehicles improve. Current diesels have a higher level of technology than most gasoline engines, as it was needed to address drivability, noise, smell, and emission concerns. As this same level of technology (direct injection, sophisticated turbocharged systems, dual-path and cooled EGR) is added to the gasoline engine, the efficiency advantage of the diesel will be much smaller. Also, BMEP can be higher on gasoline engines than on diesels, at least without additional reinforcement of the diesel engine block (cost and weight), so more downsizing is possible with gasoline.

Another consideration is that combustion technology by 2050 may blur, if not completely eliminate, the distinction between diesel and gasoline engine combustion. Given the reduced efficiency advantage of the diesel in the near future and the uncertainty about the relative benefits in the long term, there is little to be gained by adding a diesel case.

It is also not at all clear that diesels will gain significant market share in U.S. LDVs. Diesels are inherently more expensive than gasoline engines. In addition, they always operate with a lean air/fuel mixture, requiring expensive NO_x aftertreatment, and the late fuel injection creates a lot of particulates, requiring expensive particulate traps. It is expected that diesels will cost $1,500 to $2,500 more than equivalent performance gasoline engines. In most countries in Europe, gasoline taxes are higher than diesel taxes, so diesel vehicles can recoup this additional cost fairly quickly in fuel savings. However, in the United States, diesel fuel prices are higher than gasoline due to a worldwide imbalance between gasoline/diesel demand and refinery capacity. This makes for a much longer payback period that may not be acceptable to U.S. customers, especially as gasoline engine efficiency improves and hybrid alternatives come down in cost.

Engine Friction Reduction

Engine friction is an important source of energy losses. Engine friction reduction can be achieved by both redesign of key engine parts and improvement in lubrication. The major sources of friction in modern engines are the pistons and piston rings, valve train components, crankshaft and crankshaft seals, and the oil pump. Key friction reduction measures include the following (EEA, 2006):

- Low mass pistons and valves,
- Reduced piston ring tension,
- Reduced valve spring tension,
- Surface coatings on the cylinder wall and piston skirt,
- Improved bore/piston diameter tolerances in manufacturing,
- Offset crankshaft for inline engines, and
- Higher efficiency gear drive oil pumps.

Over the past two and one half decades, engine friction has been reduced by about 1 percent per year (EEA, 2006). Continuing this trend would yield about a 20 percent reduction by 2030, but considerably greater reduction than this should be possible. For example, surface technologies such as diamond-like carbon and nanocomposite coatings can reduce total engine friction by 10-50 percent. Laser texturing can etch a microtopography on material surfaces to guide lubricant flow, and combining this texturing with ionic liquids (made up of charged molecules that repel each other) can yield 50 percent or more reductions in friction.

F.1.2.2 Transmission Technologies

The primary advanced transmissions over the next few decades are expected to be advanced versions of current automatic transmissions with more efficient launch-assist devices and more gear ratios and dual clutch transmissions (DCTs). Transmissions with 8 and 9 speeds have been introduced into luxury models and some large mass market vehicles, replacing baseline 6-speed transmissions. The overdrive ratios in the 8- and 9-speed transmissions allow lower engine rpm at highway speeds, and the higher number of gears allows the engine to operate at higher efficiency across the driving cycle. Ricardo (2011) projects a 20-33 percent reduction in internal losses in automatic transmissions by 2020-2025 from a combination of advances, including improved finishing and coating of components, better lubrication, improvements in seals and bearings, better overall design, and so forth. Dual clutch transmissions, currently in significant use in Europe, will also improve with the perfection of dry clutches and other improvements, with an additional reduction in internal losses (beyond advanced automatic transmissions) of about 20 percent.

F.1.2.3 Engine Heat Recovery (Vehicle Specific)

About two-thirds of fuel energy is rejected as heat, roughly evenly divided between the engine cooling system (through the radiator) and the exhaust. Because the exhaust is at a higher temperature, heat recovery has been focused on this energy source. Most activity in this area has been focused on diesel engines used in trucks and off-road vehicles (NRC, 2010). These technologies are not applicable to BEVs or FCEVs.

- *Mechanical turbocompounding* attaches a power turbine to the exhaust to extract energy, which is coupled to the engine crankshaft. This technology, applied to a diesel engine, is in production with a reduction in fuel consumption of 3 percent. A potential for up to 5 percent reduction is claimed. Performance is best at high load operation. The technology should be applicable to gasoline engines, which have higher exhaust temperatures than diesel engines but have the disadvantage of typically operating at lower loads.
- *Electric turbocompounding* is similar to mechanical turbocompounding, but the power turbine drives a generator. The electricity can be used to supplement engine power through an electrical motor to drive accessories or to charge a battery in a hybrid system. Up to 10 percent fuel consumption reduction is predicted with 5 percent more commonly quoted. Such units are not yet available commercially.
- *Thermoelectric* power generation utilizes a direct energy conversion device, for example Bi_2Te_3, located in the engine exhaust. BMW has demonstrated this technology on a gasoline engine vehicle and projects fuel consumption reduction of 2-3 percent on the U.S. combined cycle at a power level of about 100 W (BMW, 2009). At high-load conditions, reductions of 5-7 percent are projected.

For LDV application, the most promising are the electric turbocompounding and thermoelectric technologies, used with hybrid propulsion systems, which have the necessary electric energy storage and drives. These technologies are at an early stage of development but should be commercially available by 2030. HEVs would likely benefit more than ICEVs from waste heat recovery, as generated electric power could be used in their hybrid propulsion systems or to recharge the battery. This analysis assumes waste heat recovery systems will be applied starting in 2035, and only to HEVs. The committee concluded that only mechanical turbocompounding is sufficiently advanced to be included in the study, and more efficient forms of waste heat recovery, such as Rankine cycle devices, were not included in the analyses. This report projects that 1 percent of the available combustion energy can be recovered in the midrange case and 2 percent in the optimistic case in 2050 at a cost of $200.

F.1.2.4 Performance Versus Fuel Economy

Historically, much of the improvement in efficiency has been diverted toward higher performance (i.e., weight and power), instead of improving fuel economy. It is difficult to assess the sensitivity of fuel economy to changes in performance, but it is clear that in the past up to 50 percent of the efficiency benefits may have been lost to performance increases.

The committee considered the impacts of further performance improvements in the future on the calculated efficiency estimates. It concluded that the effect of performance on fuel economy trade-off will be very different in the future for the following reasons:

1. The historical performance increases occurred primarily during periods of little regulatory pressure. The committee’s goals can only be achieved with aggressive policies, including stringent efficiency standards. Such policies will influence manufacturers to emphasize fuel economy improvements over performance improvements.
2. The average performance level of vehicles in the United States is very high, both when compared historically and when compared with other countries. Certainly additional performance increases are possible, but it is reasonable to assume that performance expectations by the average consumer are not insatiable and will eventually reach a plateau.
3. The impact of power on efficiency will decrease in the future. The downsized, boosted engines needed to meet stringent efficiency standards will have a much larger region of high efficiency operation. Currently, powerful engines running at light load are operating at much lower efficiency. Future, downsized engines will maintain much better efficiency at these low load points. In addition, hybrid systems have the ability to turn the engine off and run on the motor alone, avoiding the lowest engine efficiency regions entirely. Thus, the fuel economy impact of increasing power or engine displacement will be much smaller on future engines.
4. The fuel cell stack is more efficient at low loads. This means that more powerful fuel cell stacks will have higher efficiency during normal driving, the reverse of the ICE situation.
5. Motors are also more efficient at lower loads, so a more powerful motor will also have higher efficiency during normal driving. The effect is smaller than it is for fuel cell stacks, plus a more powerful BEV likely needs a larger battery pack, which means more weight. But, overall, there is likely to be little or no tradeoff between power and efficiency on BEVs.

Based upon the above, the committee decided that performance increases may not happen to a great degree and, if they did, would likely not have a significant impact on fuel economy in the future. More probable, under the assumptions of this study, is a reduction in performance.

Some common metrics of performance that have a direct relationship to fuel consumption include interior volume, footprint, weight, acceleration (0-60 mph time), and hill climbing (gradeability at 65 mph). Additional performance metrics, not directly related to fuel consumption but often valued by consumers, include turning radius, smoothness of ride, noise, vibration, handling, braking, headlights, seat comfort, safety, ground clearance, load carrying, towing capacity, cabin cool-down time, and more.

Fuel consumption decreases linearly with weight. Model year 2010 cars that, in general, weighed 10 percent less than average used 9 percent less fuel than average. For trucks, a 10 percent reduction in weight would yield a fuel consumption reduction of 8.3 percent.

A reduction of footprint (product of the wheelbase and track distances) by 10 percent is associated with a reduction in fuel consumption of 13.1 percent for cars and 6.5 percent for trucks. In addition, a 10 percent reduction in car interior volume came with a 1.3 percent decrease in fuel consumption.

Large fuel consumption reductions are available from downsizing at a purchase cost savings. Technology will play a role in making smaller vehicles as safe as the vehicles they replace. The attractiveness of smaller cars will be enhanced by including qualities common to larger vehicles, albeit at an increased cost.

F.1.3 Modeling Hybrid Electric Drivetrains

HEVs combine an ICE, electric motor(s), and a battery or ultracapacitor. All the energy comes from the fuel for the ICE. HEV types range from simple stop-start systems using a belt drive motor-generator[4] (or, more simply, a more powerful starter motor) and larger battery to more complex systems that allow electrical assist and/or electric drive with regenerative braking. The more complex systems, include P2 Parallel Hybrids (e.g., Hyundai Sonata hybrid), which has an electric motor inserted between the transmission and wheels, with clutches allowing the motor to drive the wheels by itself or in combination with the engine, or allowing the engine to drive the wheels without motor input; and powersplit hybrids (e.g., Prius), with two electric machines connected via a planetary gearset to the engine.

There is disagreement about the fuel consumption benefit of advanced hybrid systems in the future, because hybrid systems will improve (more efficient components, and improved designs and control strategies), but advanced engines will reduce the same losses that hybrids are designed to attack (e.g., advanced engines will have reduced idle and braking fuel consumption, yielding less benefit from stopping the engine during braking and idling). Ricardo projects 2020-2025 city cycle fuel consumption (and CO_2) benefits of 18-22 percent for P2 hybrids, 22-33 percent for power split hybrids, and some highway benefits, all compared to advanced DI engines with stop-start (Ricardo, 2011).

F.1.3.1 Estimating Hybrid System Costs

The committee considered three primary sources of information: the MIT 2007 report (Kromer and Heywood), the 2011 NRC report, and tear-down costs assessments conducted by FEV (FEV, 2012). The MIT report contains the following hybrid systems costs for a projected 2030 Toyota Camry (Kromer and Heywood, 2007, Tables 51 and 53):

- $300: Hybrid transmission/integration,
- $200: Wiring and connectors, and
- ($100): Credit for eliminating the conventional starter and alternator.

Table F.2 contains cost estimates for the manufacturing cost (without retail price equivalent) for a high-volume Prius powersplit system (2025 costs calculated based on 2008 current cost estimate and assuming 2 percent annual cost reductions through 2025 for the electric air conditioning, high voltage cables, and the body/chassis/special components and 1 percent annual cost reductions for the other components) (NRC, 2011).

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[4] The belt-drive generator system may allow some engine boosting, thus a small degree of engine downsizing.

TABLE F.2 Manufacturing Costs for Hybrid Electric Vehicle Efficiency Accessories

	2008	2025
Electrical accessories	$100	$85
Electric power steering and water pump	$200	$170
Regenerative brakes	$250	$210
Electric air conditioning	$300	$220
High voltage cables	$200	$150
Body/chassis/special components	$200	$150
Credit for starter and alternator	($95)	($95)

SOURCE: NRC (2011), Table 6.2.

TABLE F.3 Cost Estimates of Efficiency Technologies for Selected Future Hybrid Electric Vehicles

	VW Polo	VW Golf	VW Passat	VW Sharan	VW Tiguan	VW Touareg
Curb weight average, lb	2,390	2,803	3,299	3,749	3,513	4,867
System power, kW	64.6	77.8	101.2	151.1	114.6	271.8
ICE power, kW	51.7	62.3	80.9	120.9	91.7	271.8
Traction motor power, kW	12.9	15.6	20.2	30.2	22.9	54.3
High voltage battery capacity, kWh	0.74	0.86	0.99	1.12	1.05	1.43
	Cost Estimates (€)					
Torque converter—baseline (credit)	−45.89	−49.12	−53.82	−59.73	−56.00	−72.19
Service battery subsystem	− 2.43	−2.43	−2.43	−2.43	−2.43	−2.43
Alternator and regulator subsystem	−56.92	−61.23	−78.70	−82.72	−82.72	−90.55
Body system	5.83	6.10	6.24	6.39	5.56	5.89
Brake system	156.15	159.31	163.11	166.55	164.74	175.11
Electric AC compressor subsystem	101.58	106.08	111.45	115.15	117.50	135.48
Auxiliary heating subsystem	28.60	29.82	31.26	32.26	32.89	37.73
Voltage inverters/converters	81.02	88.35	110.31	117.63	117.63	128.61
Power distribution and control	140.09	143.57	147.02	150.58	146.33	152.14
TOTAL	408.04	420.44	434.43	443.68	443.50	469.78

SOURCE: FEV (2012).
NOTES: (a) System power was derived to match baseline vehicle performance. (b) Internal combustion engine (ICE) power plus motor power does not match the system power for the Touareg, because the ICE was not downsized in order to maintain the Touareg's 7,700 pound towing capability; thus, a Touareg hybrid would have better performance than a non-hybrid Touareg when not towing. (c) The euro currently is worth about $1.35.

Table F.3 provides cost estimates for each of the six vehicles evaluated for Europe (FEV's analysis for Europe is being used to be consistent with the motor cost estimates). The FEV analyses are for high-volume production, even in 2010, and are based on detailed tear-down studies of all components.

Note that the costs are reasonably consistent over different vehicles. Furthermore, the Polo is much smaller than the vast majority of vehicles in the United States. The average U.S. propulsion system power is 128 kW for cars and 167 kW for light trucks. The Sharan (151 kW) and Tiguan (115 kW) are the models with system power closest to the U.S. average, and their hybrid system costs are virtually identical. Thus, the hybrid system costs for the Sharan, with a system power in between the averages for the U.S. car and light truck, were used for all vehicles in the committee's analysis.

Battery costs and motor costs apply to all hybrid, battery, and fuel cell vehicles. Battery and motor costs are addressed below in the section on batteries.[5] This section considers the cost of the other hybrid components.

The following assumptions were made about future reductions in motor system costs:

- To reflect their relatively early stage of development for vehicles, 2 percent annual reductions in cost are applied from 2015 to 2020. After 2020, the standard annual learning cost reduction factor of 1 percent is applied.

  —For the optimistic case, a 2 percent annual learning factor was also applied for 2010 through 2015, while the mid-case costs in 2015 were assumed to be the same as in 2010.

- Hybrid systems will be increasingly used in vehicle and powertrain systems, especially after 2020. Following are the cost reductions associated with this integration.

  —Costs to modify existing vehicle bodies for the hybrid system will be eliminated starting with 2020, as electrical systems are integrated into vehicle design.

  —Coordinating regenerative braking with the standard hydraulic braking system requires a hydraulic actuator in the conventional braking circuit that regulates the amount of hydraulic pressure in the brake lines. Currently, these actuators are complicated and costly, requiring components such as a pump motor, accumulator pressure sensor, linear solenoids, changeover solenoids, wheel cylinder pressure sensors, and a master cylinder pressure sensor.[6] In the future, braking functions will be increasingly integrated into electronic vehicle controls, such as traction control, electronic stability control, and yaw and steering controls. These advanced control systems will require most of the functions currently included in the hydraulic actuator for coordinating regenerative braking. Thus, in the future much simpler systems can be used to add the coordinated regenerative braking functions. To reflect this, the cost of the brake system is assume to be half that of the current system (including learning) starting with 2020.

  —Electric air conditioning compressors are used on hybrid and electric vehicles in order to maintain air conditioning while the engine is shut off (hybrids) or does not exist (BEV/FCEV). This requires the addition of an electric motor and associated requirements. In the future, the air conditioning compressor can be integrated with the traction motor and driven mechanically by the traction motor. The cost of such systems should be equivalent to the current cost of driving mechanical compressors off of the engine. Thus, the incremental cost of the electric air conditioning compressor is assumed to be eliminated starting with 2030.

  —The credit for deletion of the torque converter will disappear as manufacturers replace conventional automatics with automated manual transmissions. On the other hand, automated manual transmissions have problems with launching vehicles from a stop, requiring special clutches to make a smooth transition. The electric motor in hybrid systems can provide full torque at zero rpm, providing a way to launch the vehicle from a stop without the need for special clutches. Thus, this credit is assumed to continue through 2050 (although discounted for learning).

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[5] Credit for a downsized engine in hybrid vehicles is explicitly calculated in the cost spreadsheet, so it is not considered in this section.

[6] T. Janello and E. Talley, "Hybrid Regenerative Braking Systems," presentations, paper 16, 2010, available at http://opensiuc.lib.siu.edu/auto_pres/16.

Another cost reduction for hybrid and PHEV vehicles is using the electric motor to fill in the torque gaps of an automated conventional manual transmission (AMT). AMTs are $150-$200 cheaper than dual-clutch transmissions (DCTs), but the long shift times and lack of engine torque during the shift makes AMTs unacceptable to most customers. Integrating an electric motor would allow the motor to fill in the torque gap and enable the use of the less expensive AMT. This is assumed to start with 2035 for the mid-case and 2030 for the optimistic case.

- Note that this credit is only for hybrids and PHEVs. It is not applied to BEVs and FCVs in the cost spreadsheets.

The results of these assumptions are detailed in Table F.4, with the first for the mid-case and the second for the optimistic case. Note that the total is only for hybrids and PHEVs. For BEVs and FCEVs, the AMT credit is removed when calculating the total cost.

Table F.5 compares the hybrid system costs to those from MIT and the 2011 NRC report. The difference is primarily due to the assumption for this analysis that there are opportunities to reduce system costs by integrating components into the vehicle and powertrain.

TABLE F.4 Cost Evolution for Hybrid Electric Vehicle Efficiency Technologies

	Torque Conv. (Credit)	Service Battery (Credit)	Alternator and Regulator (Credit)	Body System	Brake System	Electric AC Compressor	Auxiliary Heating	Voltage Inverter	Power Dist. and Control	Enable AMT (Credit)	TOTAL
Mid -Case											
2010 Baseline	($84)	($3)	($116)	$9	$233	$161	$45	$165	$211		$621
2020	($76)	($3)	($105)	$8	$105	$146	$41	$149	$191		$456
2025	($72)	($3)	($100)	$0	$100	$139	$39	$142	$181		$426
2030	($68)	($3)	($95)	$0	$95	$0	$37	$135	$172		$273
2035	($65)	($3)	($90)	$0	$90	$0	$35	$128	$164	($150)	$110
2040	($62)	($3)	($86)	$0	$86	$0	$33	$122	$156	($143)	$104
2045	($59)	($2)	($81)	$0	$82	$0	$32	$116	$148	($136)	$99
2050	($56)	($2)	($77)	$0	$78	$0	$30	$110	$141	($129)	$94
Optimistic Case											
2010 Baseline	($84)	($3)	($116)	$9	$233	$161	$45	$165	$211		$621
2020	($76)	($3)	($105)	$7	$95	$132	$37	$135	$172		$394
2025	($72)	($3)	($100)	$0	$90	$125	$35	$128	$164		$368
2030	($68)	($3)	($95)	$0	$86	$0	$33	$122	$156	($150)	$81
2035	($65)	($3)	($90)	$0	$82	$0	$32	$116	$148	($143)	$77
2040	($62)	($3)	($86)	$0	$78	$0	$30	$110	$141	($136)	$73
2045	($59)	($2)	($81)	$0	$74	$0	$29	$105	$134	($129)	$70
2050	($56)	($2)	($77)	$0	$70	$0	$27	$100	$127	($123)	$66

SOURCE: FEV (2012).

TABLE F.5 Comparison of Hybrid System Cost Estimates

	2010	2025	2030
Massachusetts Institute of Technology			$500
2011 National Research Council report	$855	$635	
Calculated mid-case	$621	$426	$273
Calculated optimistic	$621	$368	$81

TABLE F.6 Electric Motor Costs

	HEV	PHEV-10	PHEV-30	PHEV-60	BEV	FCEV
Cost	$600	$800	$800	$800	$1,400	$1,400
Size (kW)	25	38	40	42	85	90

SOURCE: Kromer and Heywood (2007).

The components of the electric motor have been around for a long time and are mature. However, vehicle applications place a premium on efficiency and on minimizing the size of the motor. This has led to new motor designs, such as more compact motor windings and connectors. Hence, motor system costs need to be assessed specifically for vehicle specific applications.

There is remarkably little information in the traditional cost literature about electric motor costs. The MIT 2007 report (Kromer and Heywood, 2007, Table 53) contains a single line about 2030 motor costs and lists the comparable motor sizes in kilowatts (kW) (Kromer and Heywood, 2007, Table 62), as shown in Table F.6. The results are fairly linear and correspond to a fixed cost of $400 and a variable cost of about $13/kW.

F.1.3.2 Electric Traction System Costs

The 2011 NRC report gave a breakout of the motor and controller costs only for the Toyota Prius.

- Motor/generator/gears were estimated to cost $1,100 in 2008 and $940 in 2025 (1 percent annual cost reduction from 2008).
- Control electronics+dc/dc (1.2 kW) were estimated to cost $1,100 in 2008 and $680 in 2025 (3 percent annual cost reduction from 2008).

A presentation by DOE to the committee included the following status and goals for PHEV electric traction systems:[7]

2008: $22/kW,
2010: $19/kW,
2012: $17/kW, and
2015: $12/kW.

The most extensive studies, by far, are the recent tear-down cost assessments conducted by FEV for the United States (funded by EPA) and for Europe (funded by the International Council for Clean

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[7] DOE EERE, “Potential for Light Duty Vehicle Technologies,” presentation to the committee, October 21, 2010.

Transportation [ICCT]) (FEV, 2012). While these studies only assessed current motor system costs, they provide detailed cost estimates for every component of the motor system. EPA and NHTSA used FEV's results, with learning applied, to estimate motor system costs for the 2017-2025 proposed vehicle standards. ICCT paid FEV to convert these results to Germany. In the course of updating the results, FEV made some changes to better reflect scaling of the tear-down results to single-motor systems and to fix a minor error. Thus, despite the additional complexity of converting the European results in euros back to U.S. dollars, the European results are used for this analysis.

Table F.7 summarizes single-motor system costs for high-volume production in 2010. Regression of the motor system cost versus the traction motor power (kW) shows an almost completely linear trend line with the equation:

2010 motor system cost = €477 + €8.27 × kW

The largest single-electric motor system assessed by FEV was 54 kW. Thus, there may be some uncertainty in extrapolating the results to the larger single-motor systems used by BEVs and FCEVs. However, in the outyears the motor sizes are smaller due to vehicle load reductions, dropping from 111 kW in 2010 to 81 kW in 2050 for cars (71 kW for the optimistic case) and dropping from 143 kW in 2010 to 116 kW in 2050 for light trucks (106 kW for the optimistic case). Thus, any errors from extrapolation should not be large.

TABLE F.7 Calculated Incremental Manufacturing Cost—P2 Hybrid Electric Vehicle Technology

	VW Polo	VW Golf	VW Passat	VW Sharan	VW Tiguan	VW Touareg
Curb weight average, lb	2,390	2,803	3,299	3,749	3,513	4,867
System power, kW	64.6	77.8	101.2	151.1	114.6	271.8
ICE power, kW	51.7	62.3	80.9	120.9	91.7	271.8
Traction motor power, kW	12.9	15.6	20.2	30.2	22.9	54.3
High voltage battery capacity, kWh	0.74	0.86	0.99	1.12	1.05	1.43
	Calculated Cost (€)					
Case subsystem	60.99	65.90	73.00	85.62	77.04	124.31
Launch clutch subsystem	40.16	42.98	47.08	52.24	48.95	68.04
Oil pump and filter subsystem	24.12	25.87	28.43	31.95	29.66	42.72
Traction motor/generator subsystem	79.97	86.59	95.43	117.52	102.06	170.54
Power electric	43.36	51.33	53.07	57.42	54.38	67.86
Control modules (motor/trans)	162.48	164.80	167.91	175.66	170.23	194.27
Traction motor-sensor subsystem	28.23	28.23	28.23	28.23	28.23	28.23
Internal electrical connections	31.97	31.97	31.97	31.97	31.97	31.97
Switch subsystem	2.28	2.28	2.28	2.28	2.28	2.28
Electrical housing/support structure	13.06	15.08	17.76	24.47	19.78	40.58
Electric motor and clutch cooling	33.56	38.55	47.08	60.12	51.50	97.47
Other miscellaneous (e.g., brackets, sealing)	1.85	1.96	2.10	2.46	2.21	3.33
OE electric motor clutch system	53.73	53.73	53.73	53.73	53.73	53.73
Total motor system cost	575.75	609.27	648.07	723.66	672.01	925.33

NOTES: (a) Data from FEV cost estimates for Europe. (b) VW Sharan used for both cars and light trucks. (c) System power was derived to match baseline vehicle performance. (d) ICE power plus motor power does not match the system power for the Touareg, because the ICE was not downsized in order to maintain the Touareg's 7,700 pound towing capability; thus, a Touareg hybrid would have better performance than a non-hybrid Touareg when not towing. (e) Euro currently about $1.35.
SOURCE: FEV (2012).

The following assumptions were made about future reductions in motor system costs:

- Motor systems for vehicles are unique due to their high efficiency and small volume requirements, as described above. To reflect their relatively early stage of development for vehicles, 2 percent annual reductions in cost are applied from 2010 to 2020. After 2020, the standard annual learning cost reduction factor of 1 percent is applied.

  —For the optimistic case, a 2 percent annual learning factor continues to be applied through 2030, after which the annual learning factor drops to 1 percent.

- Power electronics and control modules for vehicle applications are also unique, due to the high power demands and extreme conditions encountered on vehicles. These components are at a relatively early stage of development, and electronics in general have historically reduced cost more rapidly than most components. To reflect these factors, the annual cost reduction from 2010 to 2020 is doubled for power electronics and control modules from 2 to 4 percent annually. After 2020, the standard 1 percent annual cost reduction is applied to these components.

  —For the optimistic case, a 2 percent annual learning factor is applied through 2030, after which the annual learning factor drops to 1 percent.

- Some of the are due to incorporating a P2 hybrid system into an existing powertrain system (FEV, 2012). After 2020, manufacturers will start redesigning transmissions to integrate the electric motor into the transmission for P2 HEVs and PHEVs, instead of placing it between the engine and the transmission. Not only will this reduce the length of the powertrain and reduce packaging issues, but it will eliminate the need for a separate case and oil pump and filter system. It is assumed that this redesign process will be completed by 2030, with a linear incorporation from 2020 to 2030.

  —Note that this is a conservative assumption, as other motor system costs may also be reduced or eliminated by integrating the motor into the transmission, such as launch clutch system costs and motor cooling costs.

  —BEVs and FCEVs have a stand-alone motor. Thus, these cost reductions would not directly apply to them, only to HEVs and PHEVs. However, it is reasonable to assume that the scaling of case and oil pump costs will be reduced in the future. Thus, for 2030 the case and oil pump and filter system costs were assumed to drop to half of the nominal cost.

Based upon these assumptions, the fixed and variable cost coefficients for the motor system were calculated and are shown in Table F.8.

Table F.9 compares the 2030 motor system costs calculated by the above equations with the costs determined by MIT for 2030 and the 2015 DOE target.

The calculated 2030 mid-case cost for the HEV is similar to the cost calculated by MIT. While the calculated cost for the larger motors are significantly lower than MIT's, they are higher than the DOE 2015 goal for PHEV motor costs.

F.1.3.3 Electric Traction System Efficiency

Average electric motor efficiency over the test cycles was determined by the Ricardo simulation models and the EPA Energy Audit data. For the simulation modeling, Ricardo started with a motor efficiency map for the 2007 Camry (Figure F.1) (Ricardo, 2008), adjusted by reducing the losses in the motor/generator by 10 percent and reducing the losses in the power electronics by 25 percent.

EPA's Energy Audit data summed the average efficiency of the motor system over the test cycles. The P2 results for each of the six vehicle classes modeled by Ricardo were used for the 2030 mid-case motor efficiency. The efficiency of the motor system in the PHEV, BEV, and FCEV was assumed to be the same as the P2 hybrid.

Minor adjustments were made to the motor system efficiency for the other cases. Motor system losses were assumed to be 10 percent lower for the 2030 optimistic case, 20 percent lower for the 2050 mid-case, and 30 percent lower for the 2050 optimistic case.

TABLE F.8 Fixed and Variable Motor System Costs

	HEV/PHEV		BEV/FCEV	
Mid-case, US $	Fixed	Variable/kW	Fixed	Variable/kW
2010, baseline	$668	$11.58	$668	$11.58
2015, average of 2010 and 2020	$586	$10.38	$586	$10.38
2020, $4%/2% electronic/other	$504	$9.18	$504	$9.18
2025, average of 2020 and 2025	$449	$7.74	$464	$8.24
2030, 1% learning + motor integration	$393	$6.30	$425	$7.30
2035, 1% learning	$374	$5.99	$404	$6.95
2040, 1% learning	$356	$5.70	$384	$6.60
2045, 1% learning	$338	$5.42	$365	$6.28
2050, 1% learning	$322	$5.15	$347	$5.97
	HEV/PHEV		BEV/FCEV	
Optimistic Case, US $	Fixed	Variable/kW	Fixed	Variable/kW
2010, baseline	$668	$11.58	$668	$11.58
2015, average of 2010 and 2020	$586	$10.38	$586	$10.38
2020, $4%/2% electronic/other	$504	$9.18	$504	$9.18
2025, average of 2020 and 2025	$427	$7.34	$442	$7.84
2030, 2% learning+motor integration	$349	$5.50	$381	$6.50
2035, 1% learning	$332	$5.23	$362	$6.18
2040, 1% learning	$316	$4.97	$344	$5.88
2045, 1% learning	$301	$4.73	$327	$5.59
2050, 1% learning	$286	$4.50	$311	$5.32

NOTE: A ratio of $1.40: €1.00 was applied to the European results to convert into U.S. dollars. FEV used a ratio of $1.43: €1.00 to adjust the U.S. results to Germany, but the labor rates used for Germany were higher than the U.S. labor rates.

TABLE F.9 Comparison of Motor System Cost Estimates

	HEV	PHEV-10	PHEV-30	PHEV-60	BEV	FCEV
Size (kW)	25	38	40	42	85	90
MIT 2030 cost	$600	$800	$800	$800	$1,400	$1,400
DOE 2015 goal ($12/kW)	$300	$456	$480	$504	$1,020	$1,080
Calculated 2030 mid-case	$551	$633	$645	$658	$1,045	$1,082
Calculated 2030 optimistic	$487	$558	$569	$580	$933	$966

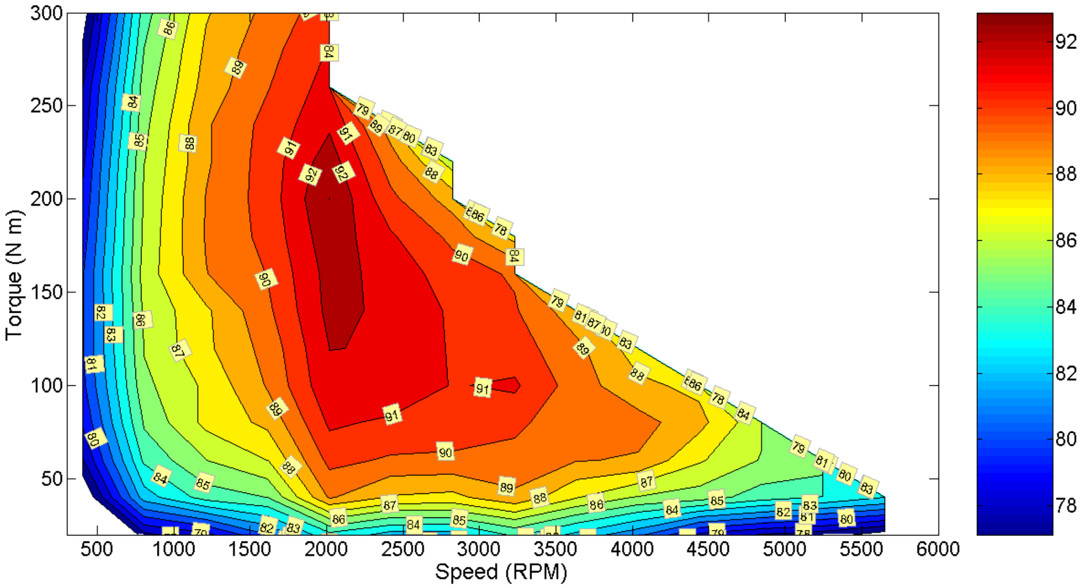

FIGURE F.1 2007 Camry Hybrid motor-inverter efficiency map.
SOURCE: Ricardo (2008).

F.1.4 A Potential Disruptive Change: Autonomous Vehicles

A possibility that could portend truly disruptive change in the LDV sector over the next few decades is the emergence of autonomous, self-driving vehicles. All major automakers, as well as transportation agencies in many countries, have research, development, and demonstration programs underway to explore intelligent transportation system (ITS) technologies. Implementing ITS is likely to require making substantial new infrastructure investments, facing the complexities of human factors and the man-machine interface, and working through numerous institutional issues about responsibility and liability for vehicles operating with varying degrees of autonomy. Nevertheless, it is likely that by mid-century some form of ITS technology will begin to reshape personal mobility.

The general concept involves cars that are still individually owned and operated but driven by computer rather than under direct human control. Although some autonomous vehicles might be part of publicly managed networks, the greatest potential for a paradigm shift is likely to involve autonomous cars that preserve the core appeal of personal mobility while freeing drivers of the time, attention, and skill required to navigate and operate vehicles themselves. Robot vehicles could be dispatched for goods movement and to securely transport non-drivers such as children, the disabled, or the elderly. Autonomous vehicles could drive on a “dumb” road infrastructure little different than today’s, but they might also evolve as part of an intelligent, energized road network. The U.S. Department of Transportation’s Research and Innovative Technology Administration (RITA) has several programs researching ITS options (DOT, 2011). The technologies involved offer the potential to dramatically improve safety, enhance mobility, and reduce congestion using strategies such as vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communications as well as robotic driving.

Autonomous vehicles are already in use on an experimental basis (Vanderbilt, 2012). At one end of the spectrum are robot vehicles having capabilities similar to today’s cars, such as the modified sport utility vehicles seen in autonomous vehicle competitions sponsored by the Defense Advanced Research Projects Agency (DARPA; Gibbs 2006). Google has been testing conventional cars with autonomous driving apparatus on public roads (Markoff, 2010). At the other end of the spectrum are small, one- or two-person podcars such as the MIT Media Lab's City Car prototypes, the General Motors Electric Networked-Vehicle (EN-V) concept, and similar ideas as discussed by Mitchell et al. (2010). Another example is Toyota's Fun-Vii concept from the 2011 Tokyo motor show, featuring more bandwidth than horsepower capability and designed for automated driving on an intelligent road infrastructure. An emphasis on a virtual environment for drivers was anticipated by Ford's concept 24-7 in 2000, and the future importance of ITS systems, including plausible timelines for implementation over the next two decades, was outlined in the "Blueprint for Mobility" announced by Bill Ford at the Mobile World Congress (Ford, 2012).

The committee did not attempt to quantify the possible impacts of autonomous cars. Not only are the characteristics of such vehicles highly uncertain, but also their effects on fuel use and GHG emissions are very difficult to project. By themselves, full-size robot vehicles (such as those of the DARPA challenge) might offer some modest efficiency gains, perhaps similar to those of optimized "ecodriving." However, networked autonomous vehicles would offer enormous safety benefits, perhaps nearly eliminating collision risks, and so could foster greater acceptance of smaller vehicles with significantly lower energy demands. Such synergies might result in automobiles with fuel consumption rates a factor of two or more below those estimated in this study. Even more dramatic reductions could be seen with small pod cars, which could cut per-mile fuel use by an order of magnitude or more compared to today's LDVs (Mitchell et al., 2010, Figure 9.18).

On the other hand, the new mobility opportunities opened up by autonomous driving could dramatically increase overall vehicle travel. For small and inexpensive robot cars, ownership and usage could rise as individuals, households, and businesses purchase multiple vehicles that might be simultaneously dispatched for numerous purposes, occupied or not. Large autonomous cars could make long trips more comfortable and enable their operators to do a wide variety of things—working, entertaining, eating, sleeping, and many other activities—when freed of the need to drive, fostering longer commutes and further dispersion of settlement. While the energy use and emissions per mile of travel might decrease, those gains could be swamped by a large increase in vehicle miles travelled. The range of possible outcomes for autonomous vehicles and how they might be used is far too vast to enable projection of their net impacts on petroleum demand and GHG emissions. Although such uncertainties preclude formal analysis, the committee recognizes that autonomous driving could well have a great transformative effect on the sector.

F.2 FUTURE VEHICLE COST AND EFFICIENCY ASSESSMENT

F.2.1 Overall Approach to Modeling

The energy required to move a vehicle is the energy delivered by the drive-train to the wheels plus the energy to operate the accessories. The drive-train energy provides multiple functions. At any instant:

$$E_{DT} = E_I + E_{HC} + E_{RR} + E_{AD} + E_A$$

where

E_{DT}	Energy delivered by the drivetrain to the vehicle wheels (total tractive energy)
E_I	Energy required to accelerate the vehicle, that is to overcome the inertia of the vehicle, which is made up of the vehicle mass plus the rotational inertia of tire/wheel/axle assemblies
E_{HC}	the energy required to provide hill-climbing
E_{RR}	Energy required to overcome the rolling resistance

E_{AD} Energy required to overcome the aerodynamic drag
E_A: Energy provided by engine for accessories (air conditioner/heat pump, power steering, power brakes, water pump, alternator, oil pump)

The energy available for overcoming inertia and hills determines the performance of the vehicle. Zero to 60 mph time in seconds quantifies vehicle acceleration. Gradeability, the grade at which a speed, often 65 mph, may be sustained, quantifies hill-climbing. The power-to-weight ratio determines both. Generally, acceptable acceleration assures acceptable hill-climbing, although this may not be the case in hybrid drivetrains with batteries that can provide power only in short bursts.

Over a driving cycle, which begins and ends at zero velocity and zero elevation change, net E_I and E_{HC} are zero, and

$$E_{DT} = E_{RR} + E_{AD} + E_A$$

The committee's analytical approach is driven by two goals. First, it is highly important that this committee present its best assessment of 2050 technology potential. Second, the modeling is kept as simple as possible to focus on the important trends rather than the unpredictable details of vehicle technology in 2050.

Projections of future ICE efficiency have generally been done by assessing the benefits of different technology pieces. Major recent reports have done detailed assessments of a broad range of technologies to improve the efficiency of ICEs and transmissions and reduced vehicle loads (NRC, 2011)

These types of assessments work well up to about 2025 or perhaps 2030. However, their usefulness for 2050 suffers from two major problems. One is that it is impossible to predict what specific technologies will be used in 2050. The second is that as we push toward the boundaries of ICE efficiency, the synergies between different technologies becomes more and more important.

The approach chosen by the committee avoided these problems by modeling vehicle loads and powertrain efficiencies and losses. Engine efficiency was assessed based on thermodynamic and engineering principles. Layered on top of this were efficiency assessments of the transmission, electric powertrain components, and fuel cell stack, as well as vehicle load assessments and recovery of energy from braking and waste heat. This ensured that synergies would be properly assessed, and the modeled efficiency results would not violate basic principles. It also facilitated the extrapolation of input assumptions for 2050 vehicles.

The primary goal of the committee was to properly assess the relative efficiency of the different technologies. Thus, care was taken to use consistent assumptions across the different technologies. For example, the same vehicle load reduction assumptions (weight, aero, rolling resistance) were applied to all of the technology packages. Engine and transmission assumptions for the ICE case were used as the starting assumptions for HEV.

Six different vehicles were modeled, a Toyota Yaris, Toyota Camry, Chrysler 300C, Saturn Vue, Dodge Grand Caravan, and Ford F-150.

Meszler Engineering Services, under contract with the NRC for this study, developed a CAFE cycle energy audit model, layered with a loss model, to calculate miles per gallon (mpg) for future vehicles and technologies. The model does not calculate efficiency directly from the inputs; rather, baseline inputs were established that corresponded with specific baseline mpg values for each of the six vehicles. The model then calculates changes in miles per gallon based on changes in input assumptions over the federal test procedure and highway cycles.

Inputs to the model were developed by the NRC committee and were reviewed by expert external reviewers. Detailed inputs were developed for vehicles with four different technologies: ICE vehicles, HEVs, BEVs, and FCEVs. PHEV operation in charge depleting mode was assumed to match the efficiency of BEVs, and operation in charge sustaining mode was assumed to match the efficiency of

HEVs, so there was no modeling specific to PHEVs. Similarly, natural gas vehicles were assumed to have the same efficiency as other ICE engines.

Variables considered by the model (not all variables were used for each technology) are as follows:

- Vehicle load reductions, such as
  —Vehicle weight,
  —Aerodynamic drag,
  —Tire rolling resistance, and
  —Accessory load;
- ICE, such as
  —Indicated (gross thermal) efficiency,
  —Pumping losses,
  —Engine friction losses,
  —Engine braking losses, and
  —Idle losses;
- Transmission efficiency;
- Torque converter efficiency;
- Electric drivetrain, such as
  —Battery storage and discharge efficiencies,
  —Electric motor and generator efficiencies, and
  —Charger efficiency (BEV only);
- Fuel cell stack efficiency, such as
  —Also the FCEV battery loop share of non-regenerative tractive energy;
- Fraction of braking energy recovered; and
- Fraction of combustion waste heat energy recovered.

The weight of the different technology packages was not adjusted to reflect the incremental weight of the technologies, such as the battery pack for BEVs. This was because the baseline efficiencies were matched to baseline vehicles, which included the incremental weight, weight reductions were input in terms of percentage weight reduction, and the battery pack sizes were scaled to efficiency improvements, implicitly scaling battery pack weight with other load reductions.

F.2.1.1 Development and Validation of Baseline Input Assumptions

Baseline inputs, including baseline mpg, for ICEs and HEVs were developed by the committee from energy audit data provided to the public by EPA, based upon computer simulation runs from Ricardo Engineering. EPA also provided public energy audit data based upon Ricardo's computer simulation for advanced ICE and HEV technology packages. These advanced ICE and HEV technologies were representative of what Ricardo and EPA determined would be available by 2020 to 2025. However, it takes at least a decade to disseminate technology across the entire vehicle fleet, so the committee used these estimates as the 2030 midrange case. The 2010 baseline and 2030 midrange model inputs were developed directly from this Energy Audit data and fed through Meszler Engineering's CAFE cycle energy audit model. The resulting mpg values were within 1 to 2 percent of the mpg results from the Ricardo simulation runs. Not only did this provide validation of the accuracy of the model, but these 2030 midrange inputs were used as the starting point for 2030 optimistic and 2050 input estimates.

The motor and battery efficiencies for BEVs and HEVs were assumed to be the same as for HEVs. The fraction of braking energy recovered was also assumed to be the same as developed for HEVs. The much larger battery packs used for PHEVs and BEVs should be able to capture higher rates of regenerative braking energy. On the other hand, a fully charged PHEV/BEV battery pack will have more limited headroom to capture high rates of regenerative braking energy. These were judged to be roughly offsetting factors.

Additional 2010 baseline input assumptions for BEVs and FCEVs were developed by Meszler Engineering Services based on public efficiency data for the Nissan Leaf, Honda Clarity, and Mercedes FCEV, including charger efficiency for BEVs and fuel cell efficiency and the battery loop share of non-regenerative tractive energy for FCEVs. These baseline inputs were developed to match public efficiency numbers for the Nissan, Honda, and Mercedes advanced vehicles and were validated by Meszler.

Development of input assumptions for the various 2030 and 2050 scenarios is described in the different technology sections, except for the 2030 midrange case for ICE and HEV, which was developed as described above. The attached Excel spreadsheet model, Appendix F Vehicle Input Spreadsheet, shows how the various vehicle characteristics were developed from the baseline.

F.2.1.2 Vehicle Cost Calculations

Costs are more difficult to assess than benefits. Every existing cost assessment is simply someone’s expert (or not so expert) opinion. The committee examined existing cost assessments for consistency and validity. Fully learned out, high-volume production costs were developed in this part of the analysis.

The primary goal was to treat the cost of each technology type as equitably as possible. Care was taken to match the cost assumptions to the efficiency input assumptions. Results from the efficiency model were used to scale the size of the ICE, electric motor, battery, and hydrogen and compressed natural gas (CNG) storage tanks (as applicable). Consistent assumptions of motor and battery costs were used for HEVs, PHEVs, BEVs, and FCEVs. HEV costs were calculated using ICE costs as the base. PHEV, BEV, and FCEV costs were calculated based on the HEV costs using inputs on battery, motor, and electronics size and cost, plus adjustments for ICE removal (BEV and FCEV), converter costs (BEV), fuel cell stack (FCEV), and gaseous storage tanks (FCEV and CNG).

Costs were calculated separately for cars and light trucks. Data from the six different vehicles analyzed for efficiency were combined, where necessary, using a simple average of the three different cars (Yaris, Camry, and 300) or three different light trucks (Vue, Caravan, and F-150). The simple averages were compared to sales-weighted average numbers from EPA’s 2010 Fuel Economy Trends Report, (EPA 2012) where averages were 6.4 percent higher than the simple average of the baseline cars and 6.9 percent higher than the simple average of the baseline light trucks. These differences will not have a significant impact on the results, especially since the offsets for the cars and light trucks were very similar.

Costs were calculated in an attached Excel spreadsheet, Appendix F Vehicle Cost Summary. Data that must be input by the user are coded in blue font. Data from other sources are in black font. These data can be modified if desired, but care should be taken, as these are generally input directly from baseline vehicle assumptions or outputs from the efficiency model. Calculations made by the spreadsheet are in red font.

This section discusses where the inputs to the spreadsheet came from and how the spreadsheet calculates costs from these inputs.

Load Reduction

The cost of lightweight materials, aerodynamic improvements, and reductions in tire rolling resistance were assumed to apply equally to all vehicles and technology types.

- User inputs:

  —Maximum proportion of weight reduction (percent of baseline vehicle weight) from high strength steel (HSS), aluminum (which includes other currently available lightweight materials such as magnesium and composites), and carbon fiber (which is only used for the 2050 optimistic case). The total amount of weight reduction must be set to be equal to the amount used for the efficiency calculations.
  —Cost of reducing a pound of weight, with separate inputs for HSS, aluminum, and carbon fiber.
  —Cost of aero improvements
  —Cost of tire rolling resistance improvements

- Other data:

  —Baseline vehicle weight is the average of the loaded vehicle weight for the 3 different models of cars or light trucks.

- Calculations:

  —Cost of each lightweight material is the % load reduction times the baseline vehicle weight times the $/pound cost.
  —Total cost is the sum of the cost of each lightweight material and tire and aero costs.

Internal Combustion Engines

This is perhaps the most subjective cost estimate, as ICE technology includes a vast array of incremental engine, transmission, and drivetrain improvements. Past experience has shown that initial costs of new technologies can be high, but generally drop dramatically as packages of improvements are fully integrated over time.

Fortunately, this is also the least important cost estimate. This is because the cost spreadsheet is set up to assess the incremental cost of other technologies relative to future ICE costs. Penetration of alternative technologies into the fleet is impacted by the difference in efficiency and cost compared to future ICEs, which is not affected by the ICE cost estimates.

- User Inputs:

  —Future ICE technology cost (including transmission and drivetrain)
  —Stop/start system cost
  —Downsized, turbocharging cost
  —Waste heat recovery cost
  —Cost credit ($ per % power reduction times number of cylinders) for downsized powertrain due to load reductions

- Other Data:

  —Number of cylinders: Average of the 3 different baseline models of cars or light trucks
  —Percent power reduction is taken from the output of the efficiency modeling

- Calculations:

—Total credit for ICE downsizing is the cost credit times the percent power reduction times the average number of cylinders.
—Total ICE cost = the sum of load reduction, ICE technology, stop/start, turbocharging, and waste heat recovery costs minus ICE credit for load reduction

HEV Costs

HEVs begin the strategy of differential costing. Costs specific to the hybrid system are added to ICE costs, and credits are subtracted to arrive at the hybrid cost increment versus ICE.

Battery, motor, and power electronics costs are treated consistently for all technology types by creating a sub-table of battery costs and motor+power electronics costs. These costs are applied consistently to all of the technology types, along with individual assessments of the battery and motor size requirements.

- User Inputs:

  —Motor+power electronics cost ($/kW)
  —Battery cost ($/kWh)
  —Motor size as % of total propulsion power
  —Battery power-to-energy ratio (kW/kWh)

- Other Data:

  —Total propulsion power (kW) is taken from the output of the efficiency modeling
  —Miscellaneous hybrid component costs and credits (assumed to be the same for all vehicles and scenarios):
    -Control electronics cost: $150
    -Wiring: $200
    -Blended brake control: $100
    -DC-DC converter: $75
    -Integration of motor into transmission: $50
    -ICE size reduction: $100 credit
    -Elimination of starter/alternator: $100 credit
    -Elimination of torque converter: $75 credit

- Calculations:

  —Motor size = Total propulsion power times motor % of total propulsion power (kW)
  —Battery size = Motor size divided by the battery power-to-energy ratio (kWh)
  —Hybrid cost = (ICE cost minus stop/start cost) plus (motor size × motor cost) plus (battery size × battery cost) plus (control electronic + wiring + blended brake control + DC-DC converter + motor integration) minus credits (ICE size reduction and elimination of starter/alternator and torque converter)

PHEV Costs

PHEV costs continue the strategy of building upon previous cost estimates, in this case building upon the HEV cost estimates.

- User Inputs:

  —Motor + power electronics cost ($/kW)

—Battery cost ($/kWh)
—Motor size as % of total propulsion power
—Battery depth-of-discharge (%)
—Electric drive range (miles) on test cycles (1.2 × desired real world range)
—On-board converter (for recharging) cost
—ICE downsizing credit (versus HEV ICE)

- Other Data:

—Total propulsion power (kW) is taken from the output of the efficiency modeling
—Energy consumption in electric-drive mode (kWh/mi) is taken from the output of the efficiency modeling.

- Calculations:

—Motor size = Total propulsion power times motor % of total propulsion power (kW)
—Battery size = BEV energy consumption times desired battery range divided by battery depth-of-discharge
—PHEV cost = (HEV cost minus waste heat recovery cost) plus (PHEV motor size × motor cost) minus (HEV motor size × motor cost) plus (PHEV battery size × PHEV battery cost) minus (HEV battery size × HEV battery cost) plus converter cost minus ICE credit for PHEV versus HEV

BEV Costs

BEV costs also build upon the HEV cost estimates.

- User Inputs:

—Motor+power electronics cost ($/kW)
—Motor size as % of total propulsion power (usually 100 percent)
—Battery cost ($/kWh)
—Battery depth-of-discharge (%)
—Electric drive range (miles) on test cycles (1.3 × desired real world range, including 10 percent reserve energy)
—On-board converter (for recharging) cost
—Credit for elimination of ICE

- Other Data:

—Total propulsion power (kW) is taken from the output of the efficiency modeling
—Energy consumption (kWh/mi) is taken from the output of the efficiency modeling.

- Calculations:

—Motor size = Total propulsion power times motor % of total propulsion power (kW)
—Battery size = Energy consumption times desired range divided by battery depth-of-discharge
—BEV cost = (HEV cost minus ICE tech, turbo, and waste heat recovery costs) plus (BEV motor size × motor cost) less (HEV motor size × motor cost) plus (BEV battery size × BEV battery cost) less (HEV battery size × HEV battery cost) plus converter cost minus credit for elimination of ICE plus ICE credit already accounted for in ICE and HEV cost estimates.

FCEV Costs

FCEV costs also build upon the HEV cost estimates.

- User Inputs:

  —Motor+power electronics cost ($/kW)
  —Battery cost ($/kWh)
  —Motor size as % of total propulsion power (usually 100 percent)
  —Fuel cell system size as % of total propulsion power
  —Fuel cell system efficiency (%)
  —Fuel cell system cost ($/kW)
  —Battery depth-of-discharge (%)
  —Battery driving range (miles) on test cycles (1.2 x desired real world range)
  —Total vehicle driving range (miles) on test cycles (1.3 x desired real world range, including 10 percent reserve energy)
  —H_2 tank cost: fixed plus $/kg of hydrogen
  —Credit for elimination of ICE

- Other Data:

  —Total propulsion power (kW) is taken from the output of the efficiency modeling
  —Energy consumption in electric-drive mode (kWh/mi) is taken from the output of the efficiency modeling.
  —Overall vehicle hydrogen consumption (kWh/mi) is taken from the output of the efficiency modeling.
  —Conversion factors for kWh of hydrogen to kg.

- Calculations:

  —Motor size = Total propulsion power times motor % of total propulsion power (kW)
  —Battery size = BEV energy consumption times desired battery range divided by battery depth-of-discharge
  —Fuel cell system power = Total propulsion power times fuel cell system size as % of total propulsion power
  —H_2 storage (kg) = Vehicle H_2 consumption rate converted to kg/mile times desired range
  —FCEV cost = (HEV cost minus ICE tech, turbo, and waste heat recovery costs) plus (FCEV motor size × motor cost) less (HEV motor size × motor cost) plus (FCEV battery size × FCEV battery cost) less (HEV battery size × HEV battery cost) plus (fuel cell system power × $/kW) minus credit for elimination of ICE plus ICE credit already accounted for in ICE and HEV cost estimates plus fixed tank cost plus (variable tank cost × kg H_2)

CNG Vehicle Costs (ICE and HEV)

CNG costs are assumed to be the same as gasoline ICE and HEV costs plus the cost of a CNG storage tank.

- User Inputs:

  —Total vehicle driving range (miles) on test cycles (1.3 x desired real world range, including 10 percent reserve energy)
  —CNG tank cost: fixed plus $/GGE of CNG

- Other Data:

  —Overall vehicle GGE consumption (gal/mi) is taken from the output of the efficiency modeling of gasoline ICE and HEV vehicles

- Calculations:

  —CNG storage (GGE) = Vehicle fuel consumption rate times the desired range
  —CNG cost = (ICE or HEV cost) plus fixed tank cost plus (variable tank cost × GGE)

F.2.2 Energy Modeling Methodology[8]

F.2.2.1 Summary of Modeling Approach

All fuel economy (and, by extension, fuel consumption) estimates discussed in Chapter 2 or this Appendix, unless otherwise noted, are intended to represent the level of fuel economy that would be achieved under the CAFE testing regime. Such levels are generally higher than the level of fuel economy that would be expected during real-world vehicle operation, but are consistent with the level of fuel economy that vehicle manufacturers would be expected to achieve in response to U.S. regulatory requirements.[9] The scenarios in Chapter 5 convert the test results to on-road fuel economy. The next section provides a brief overview of CAFE program procedures.

For this project, CAFE fuel economy was estimated using what can best be described as a two-step process. In the first step, the tractive energy required to navigate the CAFE driving cycles using a given vehicle is estimated. Tractive energy is the amount of energy that must be delivered to the wheels of a vehicle. Since CAFE testing involves defined driving cycles, and the inertial characteristics of the subject test vehicle can be measured, the energy required to navigate the driving cycles can be estimated using the fundamental physical properties of motion. While it is not the intent of this appendix to provide a detailed exposition of the associated physical properties (as these are published in any number of engineering dynamics textbooks and other reference sources), Section F.2.2.3 provides an overview of the basic properties associated with tractive energy estimation.

Once tractive energy requirements have been estimated, the second step of the modeling process involves "working backwards" from the wheels of a vehicle through the various energy transfer mechanisms (and their associated losses) to the vehicle engine (or primary energy source) to derive an associated energy input requirement (or, in more conventional terms, an input fueling rate).[10] This energy input rate can then be readily converted into an equivalent fuel economy estimate using the volumetric energy content of the associated fuel (e.g., gasoline) and the distance travelled (or, more accurately,

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[8] Section F.2.2 was provided by Dan Meszler, Meszler Engineering Services.

[9] CAFE fuel economy is generally higher than that achieved in real-world operation for several reasons, but primarily due to the fact that the driving cycles associated with CAFE testing are less demanding than those typically encountered in everyday driving and the fact that not all vehicle accessories (e.g., air conditioning systems) are operational during CAFE testing. For this reason, the fuel economy of vehicles that is published for consumer use is adjusted downward from the levels associated with the CAFE program.

[10] For a conventional internal combustion engine vehicle, the energy transfer path would proceed from the wheels through the differential, transmission, and torque converter (if present) to the flywheel. Internal engine losses associated with friction, pumping, braking (engine braking), and accessories (those that are operational during the CAFE cycles) are then accounted for to derive an estimate for the gross thermal energy available through fuel combustion. The associated input energy requirement to the engine is then estimated by applying a cycle average gross thermal (i.e., indicated) efficiency to the estimated gross thermal energy. For HEVs, an e-machine (motor/generator, controller, and enhanced battery) and its associated losses are integrated into the energy transfer path. For BEVs, the engine losses are removed and battery charger losses are added. For FCEVs, the battery charger is removed and a fuel cell system is added into the BEV energy transfer path.

simulated) over the driving cycle. Below is additional information related to this energy loss accounting as well as information on how baseline values for the various losses were estimated and validated.

The strengths and weaknesses of this two-step approach, relative to other commonly used approaches to fuel economy estimation, should be recognized. The approach employed herein is generally superior to estimation methods based on individual technology impacts or so-called lumped parameter (combined technology impact) approaches, because it explicitly limits the fuel economy improvements of "overlapping" technologies (i.e., technologies that target the same energy loss mechanism). Once losses are reduced for any given loss mechanism, those losses are not "available" for reduction to any additional technology. For example, once pumping losses go to zero, it is physically impossible to generate additional fuel economy improvements through another pumping loss reduction technology.[11] The price to be paid for this constraint is that the model user must estimate energy impacts on a loss-specific basis as opposed to the more straightforward technology basis of the alternative approaches. Model inputs are not based explicitly on the introduction of technology, but on the effects of that new technology on specific energy losses—effects that must be explicitly defined by the model user.

The two-step approach employed herein is generally less sophisticated than detailed simulation modeling, which involves defining the physical and operational characteristics of the various energy transfer processes that constitute a vehicle powertrain and then modeling energy transfer from fuel input to energy output (at the vehicle wheels). The two-step approach can be viewed as essentially a summarization of the simulation modeling process, wherein the various loss mechanisms that would be quantified through a detailed simulation model are converted to aggregate energy loss inputs for the two-step model. In effect, the two-step model, given energy loss inputs derived from a detailed simulation model, would generate the same fuel economy estimates as the simulation model. This, in fact, is the procedure that is generally used to validate the baseline fuel economy estimates from the two-step model. However, whereas the detailed simulation model would explicitly account for the effects of any new technology added to a vehicle (given an accurately developed module defining the characteristics of that technology), the two-step model accounts for the effects of that same technology through a user input estimate of the technology's effects on one or more energy loss mechanisms. Both the simulation model and the two-step model include an explicit estimation of tractive energy impacts due to changes in vehicle road load characteristics.

As is the case with actual CAFE compliance, CAFE fuel economy is estimated as the weighted average of energy (and fuel) consumption across the two driving cycles that comprise CAFE testing. The "city cycle" (i.e., the Federal Test Procedure) contributes 55 percent of overall CAFE energy requirements, while the "highway cycle" (i.e., the Highway Fuel Economy Test) contributes the remaining 45 percent. As with CAFE compliance, energy impacts associated with vehicle accessories that are not engaged during CAFE testing (e.g., air conditioning) are not captured. Independent energy consumption adjustments for these "off-cycle" loads can be calculated, but they have not been estimated explicitly through the two-step modeling approach for this project. If such adjustments are presented, the associated estimation methodology is described outside of this appendix.

In addition to the basic CAFE cycle energy analysis, the modeling work for this project also includes tractive energy evaluation over a constructed "performance cycle." The performance cycle is essentially a manufactured cycle designed to estimate the peak power required to achieve published 0-60 acceleration times for the evaluated vehicles. Tractive energy requirements are estimated over the performance cycle in exactly the same manner as described above (and detailed below) for the CAFE cycles. Estimated tractive energy required during each second of the performance cycle is equivalent to the power required during that second.[12] The maximum power estimated over the performance cycle is an indicator of the peak power required at the wheels. Peak power at the wheels is then converted into peak

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[11] Of course, it is not expected that pumping losses will go to zero (except for engineless BEVs and FCEVs); the premise is simply easiest to understand through a zero loss description.

[12] For example, power (P) in watts is equal to energy (E) in newton-meters per unit time in seconds. If we evaluate energy requirements at a frequency of 1 hertz (i.e., once per second), then $P = (E / \text{seconds}) \times 1 \text{ second} = E$.

required engine (or alternative energy source) power in exactly the same manner as described above (and detailed below) for the "second step" of the CAFE fuel economy modeling process employed for this project. This allows for a reasonable estimation of the engine (or alternative power source) peak output required to achieve the same level of vehicle performance as observed for baseline ICE vehicles. The final section of this appendix provides an expanded discussion of this peak power requirement estimation process.

F.2.2.2 Summary of CAFE Procedures[13]

CAFE testing consists of two driving cycles, one nominally intended to represent city driving and one nominally intended to represent highway driving. The ability of either cycle to accurately reflect current driving behavior is limited, and for this reason the advertised fuel economy of a vehicle is based on both CAFE and supplemental testing, but CAFE compliance is limited to these two driving cycles alone. This allows for both standardized testing and a consistent historic record, with the realization that CAFE fuel economy will be 20-30 percent higher (nominally) than actual real-world fuel economy.

The city portion of the CAFE test is based on a driving cycle known as the Urban Dynamometer Driving Schedule (UDDS). Figure F.2 graphically depicts the UDDS. City cycle testing is actually based on one complete run of the UDDS, followed by a 10 minute engine-off period, followed by a repetition of the first 505 seconds of the UDDS. For this reason, the UDDS is generally split into two components. The first 505 seconds of the cycle are known as Bag 1, with the remaining 864 seconds of the cycle known as Bag 2. The subsequent repetition of the first 505 seconds of the cycle is known as Bag 3. The "bag" terminology is derived from the fact that emissions are collected in three separate polyvinyl fluoride bags, one for each of the three portions of the cycle. In total, this three-bag cycle is known as the Federal Test Procedure. Table F.10 presents summary statistics for the UDDS, the FTP, and the component FTP bags.

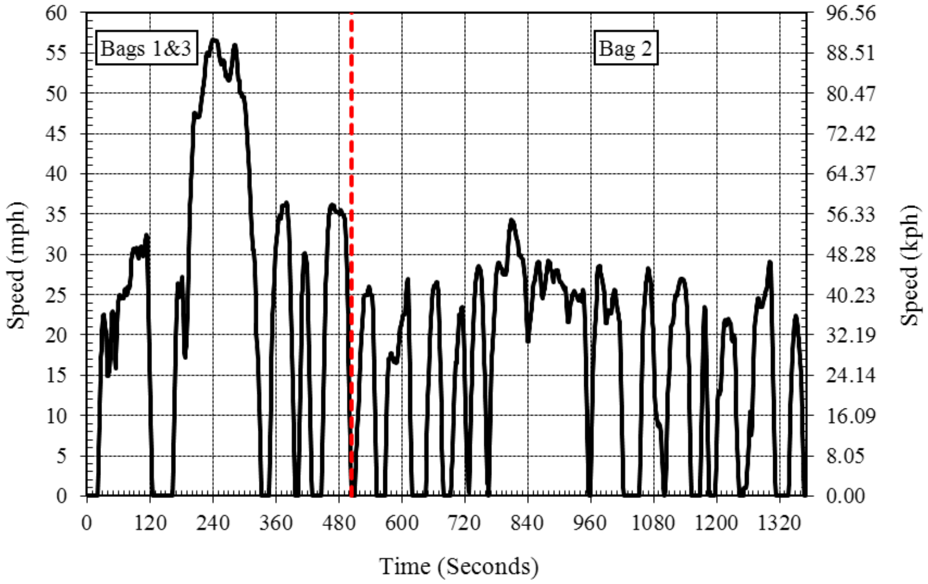

FIGURE F.2 Urban dynamometer driving schedule.
SOURCE: See http://www.epa.gov/otaq/standards/light-duty/udds.htm.

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[13] This section is intended only to provide an overview of CAFE procedures. Readers interested in further detail are referred to Title 49 Parts 523-538, Title 40 Parts 86 and 600, and Title 10 Part 474 of the Code of Federal Regulations that, in combination, define the various regulatory requirements associated with the CAFE program.

TABLE F.10 CAFE Driving Cycle Statistics

Cycle Metric	Units	Complete UDDS	FTP Bags 1&3	FTP Bag 2	Complete FTP	Complete HwFET
Cycle duration	sec	1369	505	864	1874	765
Cycle duration	min	22.82	8.42	14.40	31.23	12.75
Cycle distance	miles	7.4504	3.5910	3.8594	11.0414	10.2567
Cycle average speed	mph	19.59	25.60	16.08	21.21	48.27
Cycle maximum speed	mph	56.70	56.70	34.30	56.70	59.90
Cycle average acceleration	mph/sec	0.897	0.913	0.888	0.901	0.384
Cycle maximum acceleration	mph/sec	3.30	3.30	3.30	3.30	3.20
Cycle maximum deceleration	mph/sec	−3.30	−3.30	−3.30	−3.30	−3.30
Cycle idle time	sec	241.0	94.0	147.0	335.0	4.0
Cycle idle time	min	4.02	1.57	2.45	5.58	0.07
Fraction of cycle time at idle		17.6%	18.6%	17.0%	17.9%	0.5%

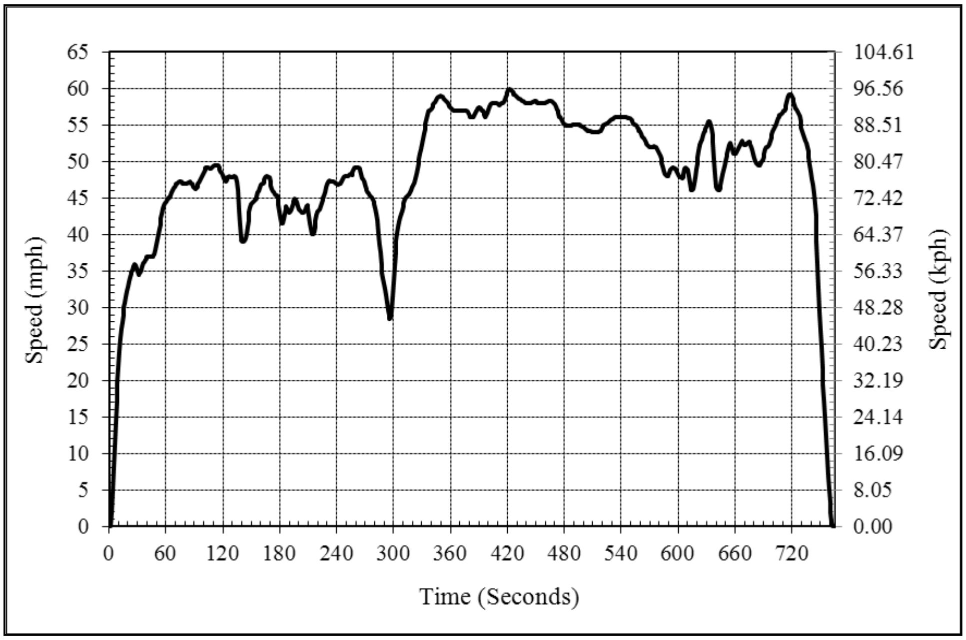

FIGURE F.3 Highway fuel economy test driving cycle.
SOURCE: See http://www.fueleconomy.gov/feg/fe_test_schedules.shtml.

The highway portion of the CAFE test is based on a driving cycle known as the Highway Fuel Economy Test (HwFET). Figure F.3 graphically depicts the HwFET. Unlike the city cycle, the highway test is run in its entirety without stop. Compared to the city cycle, the highway cycle is of generally higher speed with less transient operation. Table F.10 presents summary statistics for the HwFET.

As indicated above, CAFE is based on a 55/45 weighting of the city and highway test results. Average city cycle fuel consumption (gallons per mile, the inverse of fuel economy) is multiplied by 0.55, while average highway cycle fuel consumption is multiplied by 0.45. The results of these two operations are summed and CAFE fuel economy is equal to the inverse of the sum.

F.2.2.3 Tractive Energy Estimation

As described above, the first step in the two-step modeling approach consists of the estimation of the tractive energy required by a specific vehicle to navigate the CAFE driving cycles. For a given set of vehicle characteristics and a specified driving cycle, the tractive energy required to navigate the driving cycle is defined precisely by physics and can thus be calculated accurately (without actually testing the vehicle). Similar calculations underlie both the more detailed vehicle simulation models and the less detailed two-step model employed in this project. Given the myriad references that describe the physical theory underlying the required calculations, it is not the intent of this report to provide a robust description of either the underlying principles or the required calculations.[14] Nevertheless, a brief overview follows of the basic issues that are considered in the tractive energy calculations, as implemented in the two-step model used for this project.

To avoid any confusion with subsequent (second step) energy loss calculations, it is easiest, for tractive energy calculation purposes, to visualize the vehicle as freed of its power source and all related energy transfer technology (i.e., it is without an engine and drivetrain or other source of energy), so that its wheels are free to roll, and those wheels are themselves subject to no frictional losses in their attachment to the vehicle. Tractive energy is then the energy that must be supplied to navigate this powerless vehicle over a given driving cycle, in this case, the CAFE driving cycles described above. Since these test cycles are conducted indoors using a stationary vehicle, forces related to wind, cornering, and grade are fixed at zero.[15]

Under such conditions, the forces acting on a vehicle as it navigates a defined driving cycle are related to three influences: (1) tire rolling resistance, (2) aerodynamic drag, and (3) required vehicle motion. Tire rolling resistance is a measure of the force that must be applied to overcome the deformation characteristics of a tire (i.e., the force required to make the tire roll rather than deform). Aerodynamic drag is a measure of the force that must be applied to overcome the frictional characteristics of air (i.e., air has mass and thus induces a force that opposes vehicle motion). Vehicle motive force is a measure of the force required to induce a specified acceleration (or deceleration, which is simply a negative acceleration). Together, these three influences define the net force that must be applied to a vehicle to navigate a defined driving cycle. In mathematical terms:

$$F = R + D + M$$

where

F = the net force required to move the vehicle,
R = the force of rolling resistance,

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[14] Readers interested in detailed expositions on vehicle dynamics (which underlie the calculation of tractive energy) can consult any of a large number of available texts and reference papers. Although by no means meant to imply primacy amongst such references, examples include the following:

Thomas D. Gillespie, *Fundamentals of Vehicle Dynamics*, ISBN 1-56091-199-9, Society of Automotive Engineers, Inc., Warrendale, Pa., March 1992.

Robert Bosch GmbH, *Automotive Handbook*, 4th Edition, Stuttgart, Germany, October 1996.

Gino Sovran and Mark S. Bohn, General Motors Research Laboratories, "*Formulae for the Tractive-Energy Requirements of Vehicles Driving the EPA Schedules*," Technical Paper 810184, ISSN 0148-7191, Society of Automotive Engineers, Inc., Warrendale, Pa., 1981.

[15] Vehicle motion is simulated using a chassis dynamometer (a set of, usually floor-mounted, rollers that rotate to absorb the motion that would otherwise be imparted by a set of spinning wheels) and appropriate load settings.

D = the aerodynamic drag force, and
M = the required motive force.

Rolling resistance is primarily related to the design characteristics of the vehicle tires and vehicle mass. It is generally represented as:

$$R = (r_0 + r_1 v + r_2 v^2) \times mg$$

where

r_0, r_1, r_2 = tire rolling resistance coefficients,
v = vehicle velocity,
m = vehicle mass, and
g = gravitational acceleration (9.80665 meters per second squared).[16]

The three rolling resistance coefficients measure the design resistance of the tire. For radial tires, the velocity squared coefficient (r_2) is generally negligible and is usually ignored (as is the case for this project). The velocity coefficient (r_1) is generally numerically small relative to r_0, but can have a significant effect on overall rolling resistance as velocity increases.

Aerodynamic drag is primarily related to the airflow characteristics and frontal cross sectional area of the vehicle. It is generally represented as:

$$D = C_d \times A \times 0.5 \times v^2 \times \rho$$

where

C_d = the coefficient of drag of the vehicle,
A = the frontal area of the vehicle,
v = vehicle velocity, and
ρ = air density (1.2041 kilograms per cubic meter).[17]

The coefficient of drag can range from as low as 0.15 for an optimally streamlined vehicle to as high as 0.7 for an open convertible passenger car to more than 1 for large freight trucks. Almost all passenger cars and light trucks have coefficients in the range of 0.25-0.45. The frontal area of a vehicle represents a two-dimensional profile of the air that must be moved out of the way for the vehicle to pass. It essentially is defined by the area that is perpendicular to the line of sight of a person looking directly at an oncoming vehicle and includes the cross sectional area of protuberances such as tires, mirrors, etc. Although the precise frontal area must be measured for any given vehicle, most generally fall within a range of 80-85 percent of the product of a vehicle's geometric width and height.

The motive force is primarily related to the mass of the vehicle and the acceleration required to navigate the specified driving cycle. It is generally represented as:

$$F = m \times a = m \times (\Delta v/\Delta t)$$

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[16] Gravitational acceleration varies with one's position on the Earth, with values generally ranging from 9.78-9.82 meters per second squared. The value used for this project is the officially established value for standard gravity as set by the 3rd General Conference on Weights and Measures in 1901.

[17] Air density is influenced by ambient temperature and ambient pressure/elevation. The value presented here (and used for this project) is for standard conditions of 101.33 kilopascals and 20°C (68°F), as prescribed for constant volume sampler calibration in 40 CFR Part 86, Subpart N, §1319-90.

where

m = vehicle mass,
a = vehicle acceleration,
Δv = change in vehicle velocity, and
Δt = associated time interval.

More precisely, the change in velocity over the change in time would be expressed as the derivative dv/dt to signify the properly instantaneous nature of the force calculation. However, actual tractive energy calculations are always performed over some discrete time interval. In the case of this project, that interval is 1 second, so that the force calculations are performed once for each driving cycle second, or 1,874 times for the FTP cycle and 765 times for the HwFET cycle.

Finer resolutions are possible and are routinely employed in simulation models, but typical driving cycles (including the CAFE cycles evaluated in this study) are themselves only defined at a resolution of 1 second. Finer resolutions enable the more precise simulation of non-linear powertrain effects, but such effects are not relevant to tractive energy calculations (which are powertrain independent). Tractive energy requirements are sensitive to driver behavior, both in terms of the driver's ability to adhere to the driving cycle and in terms of driving behavior between defined cycle seconds, but fuel economy testing allows for only minor deviations from driving cycle speed/time definitions. Simulation models that include a driver module (to emulate human response to driving cycle requirements) might derive more robust tractive energy requirements than the 1-hertz model employed for this project, but any increase in precision is only as "good" as the driver module itself, and the magnitude of any deviations should be minor by definition. For comparative purposes, the tractive energy requirements calculated for the six vehicle platforms evaluated in this project (see below for a description of the six platforms) were compared to corresponding tractive energy requirements predicted by a high resolution vehicle simulation model. All six tractive energy calculations agreed to within ±3 percent, and all were ultimately calibrated to agree to within ±0.05 percent so that any predicted changes in tractive energy requirements (due to forecasted changes in vehicle load parameters) are expected to be quite accurate.[18]

The use of vehicle mass in the motive force equation is also somewhat imprecise, because each tire also possesses rotational inertia that must be overcome to induce motion. The mass equivalent of this rotational inertia (for a single tire) is calculated as:

$$m_{rot} = I / (rr^2)$$

where
m_{rot} = rotational inertia equivalent mass,
I = tire rotational inertia, and
rr = tire rolling radius.

The equivalent mass imparted by four tires is four times m_{rot}, so that the total mass associated with the motive force is $m + 4\ m_{rot}$, and the overall motive force is:

$$F = (m + 4\ m_{rot}) \times (\Delta v/\Delta t)$$

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[18] Although not investigated completely due to limitations in the type of data available for the simulation modeling runs, it is believed that the magnitude of the tractive energy deviations is more dependent on differences in the assumed vehicle load parameters for each of the six vehicle platforms than on any difference in the tractive energy calculations themselves.

It is this more precise definition that is applied for this project, although the difference between the less and more precise definitions is generally minor, as the mass due to rotational inertia is small compared to typical vehicle mass (typically less than 3 percent and smaller still for high mass vehicles). Nevertheless, this relationship can vary, especially if mass reduction technology is employed in an aggressive fashion, so the more precise rotational effects are considered.

As indicated, the net force required to navigate a specified driving cycle is dependent on several vehicle characteristics—namely, the tire rolling resistance coefficients, vehicle mass, the vehicle coefficient of drag, vehicle frontal area, tire rotational inertia, and tire rolling radius—and several parameters associated with the specified driving cycle—namely, velocity and acceleration per unit time. These latter parameters are defined by the driving cycle itself, and for this project represent the characteristics of the two CAFE driving cycles as depicted above. Table F.11 presents the former vehicle-specific parameters (under baseline conditions) that have been assumed for this project.

Tractive energy is the energy expended in exerting the force required to navigate a driving cycle over the distance associated with that cycle. Since driving cycles are generally defined in terms of velocity and time (rather than distance), it is convenient to express distance in terms of velocity and time (as distance = velocity × time) and tractive energy as:

$$TE = F \times s = F \times v \times t$$

where

F = the net force required to move the vehicle,
s = the distance over which the force is applied,
t = the time interval over which the force is applied, and
v = vehicle velocity over the time interval.

As with the force calculation, the precise energy calculation would be expressed as the instantaneous energy required for a given instantaneous force and time. Total tractive energy is then the sum (or integration) of this instantaneous energy over an entire specified driving cycle. In keeping with the 1 hertz nature of the force calculations, the energy calculations for this project are also performed once per second and summed over the driving cycle to obtain the total estimated tractive energy required to navigate the cycle.

This estimated tractive energy is the amount of energy that must be available at the vehicle's wheels. Given this value, it is possible to "work backwards" from the wheels through a vehicle's drivetrain and engine (or alternative energy source) to derive the required amount of energy that must be input into the engine (or alternative energy source). This "path backwards" represents the second step of the two-step modeling process, as described in more detail below. Once the required input energy is "known" (i.e., estimated), it is a simple arithmetic exercise to convert input energy into fuel economy (which is essentially energy per unit distance, with the latter being defined by the specific driving cycle evaluated).

Although not critical to determining overall input energy requirements, there are a few component calculations inherent in the tractive energy estimation process that are helpful in the estimation of certain energy transfer inputs used in the second step of the modeling process. Therefore, these calculations are discussed briefly here. Such calculations are also useful in understanding the tractive energy impacts of changes in vehicle load characteristics (e.g., rolling resistance, aerodynamic drag, vehicle mass).

TABLE F.11 Baseline Vehicle Tractive Energy Parameters

Parameter	Units	Toyota Yaris	Toyota Camry	Chrysler 300	Saturn Vue	Grand Caravan	Ford F-150
r_0 coefficient		0.009402	0.008223	0.011288	0.006913	0.007207	0.008245
r_1 coefficient	sec/m	2.36E-05	4.24E-06	4.99E-05	0.000181	0.000165	0.000111
r_2 coefficient	sec^2/m^2	0	0	0	0	0	0
C_d coefficient		0.32	0.30	0.33	0.37	0.34	0.41
Frontal area	ft^2	24.76	24.76	25.83	26.91	30.14	35.20
Frontal area	m^2	2.30	2.30	2.40	2.50	2.80	3.27
Vehicle mass	pounds	2,625	3,625	4,000	4,000	4,500	6,000
Vehicle mass	kg	1,190.7	1,644.3	1,814.4	1,814.4	2,041.2	2,721.6
Rolling radius[a]	m	0.282	0.320	0.342	0.340	0.330	0.382
Rotational inertia[a]	$kg\text{-}m^2$	0.56	0.90	0.97	0.95	0.94	1.00
Rotational mass[b]	kg	28.17	35.16	33.17	32.87	34.53	27.41
Effective mass	kg	1218.9	1679.4	1847.6	1847.3	2075.7	2749.0
Rotational mass factor		1.024	1.021	1.018	1.018	1.017	1.010

[a] Per tire.
[b] Total for four tires.

Any given driving cycle can be summarized in terms of three basic energy modes: (1) an energy input mode, during which tractive energy must be supplied to meet the velocity requirements of the cycle, (2) an energy output (or dissipative) mode, during which tractive energy must be removed to meet the velocity requirements of the cycle, and (3) a zero energy mode, during which tractive energy is neither supplied or removed. The zero energy mode basically occurs when a vehicle is idling during the periods of a driving cycle where the demanded velocity is zero.[19]

Energy input modes occur during the acceleration and cruise (constant velocity) portions of a driving cycle, wherein tractive energy must be supplied to overcome opposing road load forces and, in the case of acceleration, to supply the required motive force.[20] Energy input is also required during vehicle deceleration events in which road load forces are sufficiently large so that inertial momentum is not sufficient to maintain the velocity required by the driving cycle without additional energy input. Such powered deceleration events are not uncommon (throttle is reduced, but not closed).

Energy output modes occur during decelerations in which road load forces are not large enough to slow the vehicle as rapidly as the driving cycle demands. Some form of braking must occur during such

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[19] It is also possible that a vehicle may encounter a brief zero energy demand condition during a deceleration in which road load forces are exactly offset by unpowered inertial momentum. Such encounters are both rare (since the driving cycle deceleration profile must *exactly* balance the encountered road load forces) and vehicle specific (since the inertial and road load forces of one vehicle are unlikely to *exactly* match those of another). Such non-idle zero energy modes are *not* the same as closed throttle “coasting” events, but rather constitute a very small subset of such events, wherein the small amount of motive energy provided at closed throttle is *exactly* balanced by opposing road load forces plus inertial deceleration forces. In the vast majority of closed throttle “coasting” events, these forces will not be in balance and “engine” braking (an energy output mode) will occur. Closed throttle coasting is not typically a zero energy mode.

[20] Road load forces are defined as the sum of rolling resistance and aerodynamic drag forces, signifying those forces that arise independent of the specific motive force demands of a driving cycle.

modes so that tractive energy is removed faster than can be accomplished through the combination of inertial and road load forces. This braking can be limited to engine braking in instances where drivetrain inertia is sufficiently large to impart the necessary deceleration, or involve wheel-based friction braking in instances where additional tractive energy must be removed to impart the required deceleration.

During tractive energy analysis, each component of a driving cycle (meaning, in the case of this project, each second of the driving cycle) is determined to be in one of these energy modes, so that when integrated across the entire cycle, the energy input and output fractions are clearly identifiable, as are the individual motive, rolling resistance, and aerodynamic drag-induced components of those fractions. One consequence of this is that the fraction of tractive energy that is dissipated through braking is quantified. This fraction, in combination with the overall tractive energy estimate, dictates the *maximum* amount tractive energy that can be recovered through regenerative braking technology. Properly applying this maximum recovery fraction to regenerative braking calculations associated with this project ensures that such calculations are properly bounded and do not inherently overestimate potential braking energy recovery.

A second, less obvious, consequence of the detailed tractive energy analysis is that the effects of changes in specific vehicle load parameters, as well as their interactions, can be fully understood. Although such effects are generally considered to be intuitively obvious, that is not always the case, and, additionally, synergistic effects can be masked without a detailed understanding of the various tractive energy modes.

Since, as shown above, the total tractive force (F) is equal to the *arithmetic sum* of the rolling resistance (R), aerodynamic drag (D), and motive (M) forces, the impacts on these three component forces (and their associated energies) are also *additive*. In other words, changes to vehicle load parameters generally impart non-overlapping influences on the energy required to move the vehicle.[21] For example, reducing the rolling resistance force does not diminish the potential force reduction that can be achieved through reductions in the aerodynamic drag force. The forces are *not* multiplicatively related, as is the case for many technology implementations.[22] This additive relationship has a few subtle effects that must be understood to fully appreciate tractive energy impacts.

It is desirable to be able to develop generalized relationships between a change in individual load parameters and the impact of that change on overall tractive energy (e.g., if rolling resistance is reduced by X percent, tractive energy requirements are reduced by Y percent). It is similarly desirable to be able to develop a generalized estimate of the tractive energy impact of changes in multiple load parameters. Unfortunately, the additive nature of the tractive force components renders such relations inherently imprecise. That is not to say that rules-of-thumb cannot be developed or that precise measures cannot be developed for a *given set of vehicle characteristics*, it is simply that precision is dependent on such characteristics, and, therefore, the precise relationships are inherently vehicle-specific.

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[21] There is an exception to this in the case of changes to vehicle mass (which affects both rolling resistance and motive force), and this is considered fully in the discussion that follows. However, for the introductory purpose of distinguishing the additive nature of vehicle load impacts, in contrast to an alternative multiplicative relationship wherein individual absolute impacts are dependent on implementation order, it is convenient to ignore the fact that changing mass affects both the motive and rolling resistance load parameters.

[22] Take, for example, two technologies that improve vehicle driveline efficiency, say, through reductions in torque converter and transmission losses. In this case, the individual improvements target the *same* overall driveline losses, and once the efficiency of the torque converter is improved, the driveline losses available for reduction through transmission improvements are smaller than they would have been in the absence of the torque converter improvements. In effect, the absolute magnitude of the energy loss reductions associated with the installation the improved transmission are smaller if that transmission is installed with the improved torque converter than without. In this case, the improvements are multiplicatively related (i.e., their individual impacts cannot be arithmetically summed). This is true of any improvements that target the same energy losses, be those losses in the driveline, in the engine (e.g., pumping or friction losses), or anywhere else in the chain of processes that convert fuel energy to tractive energy.

The independence of individual tractive force components and the vehicle-dependent nature of the impact of changes to the individual tractive force components on the total tractive force (and, thus, on total required tractive energy) is perhaps most understandable mathematically. As discussed above, the tractive force relationship is:

$$F = R + D + M$$

If we implement a reduction of 40 percent in the rolling resistance force component, the new total tractive force becomes:

$$F_{new} = (0.6 \times R) + D + M$$

and the impact on the total tractive force is:

$$(F_{new}/F) = [(0.6 \times R) + D + M] / [R + D + M]$$

In the absence of knowledge of the relationship between the rolling resistance (R), aerodynamic drag (D), and motive (M) forces, it is simply not possible to derive a precise numerical estimate for the change in the total tractive force (F_{new}/F). And, since the relationship between R, D, and M is vehicle dependent, the change in the total tractive force (F_{new}/F) is also vehicle dependent. The only exception to this is the constrained case where the identical reduction is applied to all three force components. In this case, the new total tractive force becomes:

$$F_{new} = (X \times R) + (X \times D) + (X \times M) = X \times (R + D + M)$$

where

X = 1 minus the percent reduction in force.

and the impact on the total tractive force is:

$$(F_{new}/F) = [X \times (R + D + M)] / [R + D + M] = X$$

So that the resulting reduction in the total tractive force is identical to that of the component forces.

Since the component forces are vehicle specific, it is perhaps informative to look at example impacts for a single vehicle. Suppose that vehicle has a tractive energy relationship as follows (in F = R + D + M format):

$$2.032793709 = 0.517590608 + 0.644968344 \qquad + 0.870234757$$

In this case:

$$R/F = 0.517590608 / 2.032793709 = 25.462\%,$$
$$D/F = 0.644968344 / 2.032793709 = 31.728\%$$
$$M/F = 0.870234757 / 2.032793709 = 42.810\%$$

Based on these relationships, a 40 percent reduction in the rolling resistance force component can now be translated into a total tractive force impact as follows:

$$(F_{new}/F) = [(0.6 \times R) + D + M] / F = (0.6 \times R/F) + D/F + M/F$$
$$(F_{new}/F) = (0.6 \times 0.25462) + 0.31728 + 0.42810 = 0.898152$$

So, a 40 percent reduction in the rolling resistance force results in a 10.2 percent reduction in total tractive energy (or a 2.5 percent total tractive force reduction per 10 percent reduction in rolling resistance force). We can, of course, apply the same 40 percent component force reduction to the aerodynamic drag and motive force components individually and derive the following:

$$(F_{new}/F) = 0.25462 + (0.6 \times 0.31728) + 0.42810 = 0.873088$$
$$(F_{new}/F) = 0.25462 + 0.31728 + (0.6 \times 0.42810) = 0.828760$$

and derive a 3.2 percent total tractive force reduction per 10 percent reduction in aerodynamic drag and a 4.3 percent total tractive force reduction per 10 percent reduction in motive force. However, this latter motive force reduction is misleading for two reasons. First, the driver of the motive force reduction is an underlying change in vehicle mass (since the acceleration component of the force is fixed by the driving cycle). Since mass affects both the motive and rolling resistance forces, a change in vehicle mass cannot affect the motive force alone. Second, a 40 percent reduction in motive force is not equivalent to a 40 percent reduction in vehicle mass due to the small mass influence of tire rotational inertia. If we instead specify the motive force reduction in terms of a 40 percent reduction in vehicle mass, the equivalent overall (vehicle plus rotational inertia) mass reduction is 39.16 percent (for this example). If we plug these complete mass impacts into the tractive force equations, we get:

$$(F_{new}/F) = (0.6 \times 0.25462) + 0.31728 + (0.6084 \times 0.42810) = 0.730508$$

which equates to a 6.7 percent total tractive force reduction per 10 percent reduction in vehicle mass. To reiterate, however, these relationships *are vehicle specific* and will vary in accordance with the relative relationships between the rolling resistance, aerodynamic drag, and motive forces for any given vehicle.

A less significant, but nonetheless confounding, influence on the relationship between the total tractive force and changes in the three force components, results from the impact that changes in the individual components have on the relationship between powered (energy input) and braking (energy output) deceleration. The amount of powered versus braking deceleration for a vehicle (over a specified driving cycle) is determined by the sum of the three force components relative to driving cycle requirements. Changing one or more of the force components can affect the amount of powered deceleration, which induces a secondary effect on total tractive energy that leads to some (generally minor) variation from the arithmetically derived effects estimated above.

Take for example, a reduction in vehicle mass without any change in vehicle rolling resistance or aerodynamic drag parameters (except for the effect that changing mass itself has on rolling resistance). During high-speed decelerations, aerodynamic drag dominates road load forces, and since it is unaffected by the change in vehicle mass, it leads to a larger net deceleration force (since inertial momentum forces have decreased) for the reduced mass vehicle (as compared to the same vehicle at its original mass). This results in a shift in the deceleration energy modes (again relative to the mode fractions for the vehicle at its original mass) away from braking (energy out) deceleration and toward powered (energy in) deceleration. The net motive energy actually declines by an amount larger than the mass reduction would imply, since motive force is negative during these “added” powered decelerations, but this is offset by increases in the rolling resistance and aerodynamic drag energy associated with the “added” powered decelerations.[23] The net effect on total tractive energy is minor (generally less than 1 percent), but, nonetheless, affects the otherwise straightforward arithmetic estimation process.

For example, if we compare the tractive energy for the same vehicle used in the arithmetic example above, we find that a 40 percent reduction in vehicle mass (a net mass reduction of 39.16 percent) with no additional rolling resistance or aerodynamic drag influences decreases motive force by 43.3 percent, as compared to an expectation of 39.16 percent in the absence of any shift in powered

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[23] In the case of rolling resistance, the increase is relative to the tractive energy that would be expected after the change in vehicle mass is applied, not relative to a pre-mass reduction baseline.

deceleration requirements.[24] This is offset by 3.4 and 3.7 percent increases in rolling resistance and aerodynamic drag energy requirements, respectively, as compared to the energy that would be required in the absence of any shift in powered deceleration requirements. The net effect on total tractive energy is only about 0.1 percent (as compared to the nominal effect that would be expected in the absence of any shift in powered deceleration requirements).

Exactly the opposite occurs for changes in rolling resistance or aerodynamic drag without any change in vehicle mass. In both cases, reduced road load forces shift deceleration toward more braking. This eliminates some of the negative motive energy that accrues during powered decelerations, thus increasing motive energy (by 2.8 and 4.5 percent, respectively, for a 40 percent reduction in rolling resistance and aerodynamic drag forces).[25] For the rolling resistance reduction, this is offset by 2.5 and 2.3 percent decreases in rolling resistance and aerodynamic drag energy requirements, respectively, as compared to the energy that would be required in the absence of any shift in powered deceleration requirements. The aerodynamic drag reduction induces corresponding changes of 3.5 and 4.5 percent. The net effect on total tractive energy is only about 0.1 and 0.2 percent, respectively, for the rolling resistance and aerodynamic drag changes (as compared to the nominal effect that would be expected in the absence of any shift in powered deceleration requirements).

If rolling resistance, aerodynamic drag, and vehicle mass are simultaneously reduced by 40 percent (rolling resistance force is actually reduced by 64 percent due to the added mass effect on rolling resistance), then a shift toward more braking deceleration is observed (42 seconds more of braking over both CAFE cycles 32 seconds for the city cycle and 10 seconds for the highway cycle, which equates to a shift of 4.4 percent of total deceleration time or 4.9 and 3.4 percent, respectively, for the city and highway cycles). This decreases rolling resistance and aerodynamic drag energy requirements by 2.6 and 2.4 percent respectively, as compared to the energy that would be required in the absence of any shift in powered deceleration requirements. Motive energy requirements increase by 1.5 percent. The net effect on total tractive energy is about 0.6 percent, as compared to the nominal effect that would be expected in the absence of any shift in powered deceleration requirements.

The bottom line is that such “subtle” effects can (and do) influence energy parameters in multiple ways, including the amount of energy available for regenerative braking and the net tractive energy impact of changes in vehicle load parameters. While it is not critical that the reader understand these various nuances, it is important that they recognize that such nuances exist and have the potential to induce “synergistic” effects on tractive and braking energy requirements.

F.2.2.4 Energy Input and Fuel Economy Estimation

Following the “first step” estimation of tractive energy requirements, the modeling process employed for this project implements a “second step” that involves “working backwards” from the wheels of a vehicle through the various energy transfer mechanisms (and their associated losses) to the vehicle engine (or primary energy source) to derive an associated energy input requirement (or, in more conventional terms, an input fueling rate). This energy input rate can then be readily converted into an equivalent fuel economy estimate using the volumetric energy content of the associated fuel (e.g., gasoline) and the distance travelled (or, more accurately, simulated) over the CAFE driving cycles. Table

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[24] The mass reduction results in an increase in powered deceleration by 49 seconds over both CAFE cycles (29 seconds for the city cycle and 20 seconds for the highway cycle), which equates to a shift of 5.1 percent of total deceleration time (4.4 and 6.7 percent, respectively, for the city and highway cycles).

[25] The 40 percent rolling resistance reduction results in a decrease in powered deceleration by 40 seconds over both CAFE cycles (31 seconds for the city cycle and 9 seconds for the highway cycle), which equates to a shift of 4.2 percent of total deceleration time (4.7 and 3.0 percent, respectively, for the city and highway cycles). The 40 percent aerodynamic drag reduction results in a decrease in powered deceleration by 45 seconds over both CAFE cycles (27 seconds for the city cycle and 18 seconds for the highway cycle), which equates to a shift of 4.7 percent of total deceleration time (4.1 and 6.1 percent, respectively, for the city and highway cycles).

F.12 presents a simplified example of this “second step” process for a hypothetical ICEV. Actual calculations are more detailed, as required to accurately capture the complete energy transfer path of all powertrain components, but the basic process is identical to that shown.

The specific energy transfer pathways modeled for each of the four vehicle architectures investigated in the project (ICE vehicles, HEVs, BEVs, and fuel cell vehicles) are discussed individually in this report.

Internal Combustion Engine Vehicles

The energy transfer path for ICEVs, as implemented for this project, includes the various components and energy loss mechanisms specified in Table F.13. To implement the model algorithms for this project, a tailored energy loss mechanism impact input format was developed. The specific format (and values for each modeled scenario) of the various data inputs are shown in the body of the report, but those inputs are structured, as indicated in Table F.14. Note that not all (or even any) vehicles may have all of the components for which associated inputs are available. In such cases, the model is “instructed” to ignore these components either by the input of an efficiency of 100 percent or the input of zero value energy capture. For example, a vehicle without a torque converter is simply modeled as through it has a 100 percent efficient torque converter, as a lossless component is no different (from an energy standpoint) than no component. Similarly, if no braking or waste heat energy is recovered, then it makes no difference what the efficiency of an ICE e-machine is, as there is no energy being routed through the machine (of course, in reality the e-machine itself would not exist, but for energy consumption purposes, this is functionally identical to a zero energy transfer state).

TABLE F.12 Simplified Example Input Energy (Fuel Economy) Calculation

ID	Estimate	Units	Energy Path Component Description
A	0.2	kWh/mi	CAFE tractive energy requirement
B	0	kWh/mi	Braking energy recovered
C	0	kWh/mi	Waste heat energy recovered
D	0.2	kWh/mi	Required energy from transmission (= A − B − C)
E	88%		Transmission efficiency
F	0.227273	kWh/mi	Required energy from torque converter (= D/E)
G	93%		Torque converter efficiency
H	0.244379	kWh/mi	Required energy from engine (= F/G)
I	0.2	kWh/mi	Parasitic engine losses [b]
J	0.444379	kWh/mi	Required fuel combustion energy (= H + I)
K	38%		Gross thermal efficiency of engine
L	1.169419	kWh/mi	Required energy into engine (= J/K)
M	34.19068	kWh/gal	Gasoline energy content (= 116,663.4 Btu/gal)
N	29.23732	mpg	CAFE fuel economy (= M/L)
O	20.9%		Brake thermal efficiency of engine (= H/L)
P	17.1%		Tractive efficiency of vehicle (= A/L)

NOTE: kWh = kilowatt-hours; mi = miles; gal = gallon; mpg = miles per gallon.

[a] Pumping plus friction plus engine braking plus accessory losses.

TABLE F.13 Internal Combustion Engine Vehicle Energy Losses

Vehicle Component	Energy Loss Mechanism	Brief Description of Loss Mechanism
Internal combustion engine	Gross (Indicated) efficiency	Energy lost in the thermal conversion of fuel energy to mechanical energy.
	Pumping losses	Energy used internally by the engine to move and compress air and move combustion products. These losses are subdivided into losses during periods of idling and non-idling.
	Friction losses	Energy used internally to overcome friction. These losses are subdivided into losses during periods of idling and non-idling.
	Braking losses	Energy consumed during periods of engine braking.
	Accessory losses	Energy used to power vehicle accessories.[a] These losses are subdivided into losses during periods of idling and non-idling.
Driveline	Torque converter losses	Losses due to all inefficiencies associated with the transfer of energy from the engine flywheel to the transmission.
	Transmission losses	Losses due to all inefficiencies associated with the transfer of energy from the torque converter to the wheels (including differential losses).
Electric machine (if present)	Vehicle braking recovery	Braking energy input into a driveline generator for storage and subsequent reuse (negative losses). It is assumed that recovered energy (if any) is “injected” into the driveline upstream of the torque converter and is thus subject to both e-machine and driveline losses.
	Waste heat recovery	Waste heat energy input into an electrical generator for storage and subsequent reuse (negative losses). It is assumed that recovered energy (if any) is “injected” into the driveline upstream of the torque converter and is thus subject to both e-machine and driveline losses.
	Generator losses	Energy lost in the conversion of mechanical braking energy to electrical energy.
	Battery storage losses	Energy lost in the conversion of electric energy to chemical energy.
	Battery discharge losses	Energy lost in the conversion of chemical energy to electric energy.
	Motor losses	Energy lost in the conversion of electrical energy to mechanical energy.

[a] For this project, this includes only accessories that are operational during the CAFE driving cycles.

TABLE F.14 Internal Combustion Engine Vehicle Input Parameters

Input Parameter	Application Methodology
Rolling resistance multiplier	Multiplier applied to baseline rolling resistance coefficients.
Aerodynamic drag multiplier	Multiplier applied to the baseline aerodynamic drag coefficient.
Vehicle mass multiplier	Multiplier applied to the baseline vehicle mass (affects both motive and rolling resistance forces).
Fraction of braking energy recovered	Represents the fraction of total braking energy that is input into an e-machine generator for subsequent consumption. It is assumed that energy output from the e-machine is "injected" into the drivetrain upstream of the vehicle transmission (and torque converter if present).
E-Machine generator efficiency[a]	Change in baseline efficiency or losses.
Battery storage efficiency[a]	Change in baseline efficiency or losses.
Battery discharge efficiency[a]	Change in baseline efficiency or losses.
E-Machine motor efficiency[a]	Change in baseline efficiency or losses.
Transmission efficiency[a]	Change in baseline efficiency or losses.
Torque converter efficiency[a]	Change in baseline efficiency or losses.
Engine pumping loss improvement	Percentage reduction in baseline losses.
Engine friction loss improvement	Percentage reduction in baseline losses.
Cycle average accessory power	Compared to baseline values to derive percentage reduction in baseline engine-driven accessory losses.
Engine braking loss improvement	Percentage reduction in baseline losses.
Additional idle loss improvement	Percentage reduction in baseline idle losses, applied after the impacts of any pumping, friction, and accessory loss improvement.
Gross thermal efficiency[a]	Change in baseline indicated efficiency or losses.
Fraction of combustion waste energy (heat) recovered	Represents the fraction of total combustion waste heat, both through coolant and exhaust, recovered. Any losses associated with the heat capture device itself should be explicitly accounted for in the specified fraction of energy captured. It is assumed that the capture device routes its output energy to an e-machine that subsequently "injects" its output energy into the driveline upstream of the vehicle transmission (and torque converter if present).

[a] The inputs are actually structured to allow the user to either: (1) enter a specified reduction in baseline vehicle component losses, (2) enter a specific efficiency, or (3) enter a specified percentage change in baseline vehicle component efficiency. Appropriate error checking is implemented to ensure that any specified percentage changes in efficiency do not increase efficiency above 100 percent.

TABLE F.15 Internal Combustion Engine Vehicle Simulation Modeling Results

Vehicle	Configuration	Simulated CAFE mpg	Target CAFE mpg[a]	Official 2009 CAFE mpg[b]	Simulation Relative to Target (%)	Simulation Relative to Official (%)
Toyota Yaris	1.5 L A4 FWD	41.2	41.4	41.9	−0.5	−1.7
Toyota Camry	2.4 L A5 FWD	32.0	32.0	32.9	+0.0	−2.7
Chrysler 300	3.5 L A5 RWD	25.5	25.3	25.8[c]	+0.8	−1.2
Saturn Vue	2.4 L A4 FWD	28.8	28.3	28.4	+1.8	+1.4
Dodge Grand Caravan	3.8 L A4 FWD	23.1	23.6	23.8[d]	−2.1	−2.9
Ford F-150	5.4 L A4 4WD	17.6	18.1	19.6[e]	−2.8	−10.2

[a] Target fuel economy is that which was reported by the simulation modeler. As indicated, there is sometimes considerable difference between the reported target and the official CAFE data for 2009, which represents the model year nearest to the time the simulation modeling was performed.
[b] Source: http://www.fueleconomy.gov/feg/download.shtml, 2009 Datafile.
[c] Data is for 3.5 L A4 RWD. No 3.5 L A5 RWD configuration was reported.
[d] Data is for 3.8 L A6 FWD. No 3.8 L A4 FWD configuration was reported.
[e] Data is for 5.4 L A6 AWD. No 5.4 L A4 4WD configuration was reported.

The baseline loss estimates for the second (energy accounting) step of the two-step modeling process were established using simulation modeling results that have been reported for the six vehicles investigated in this project (NHTSA-EPA, 2010b). Table F.15 summarizes the fuel economy data associated with the simulation modeling. As indicated, there are some differences between the CAFE fuel economy targets reported by the simulation modelers and those reported in the official CAFE data. The source of these discrepancies is not clear, but it is clear that the simulation model was calibrated to produce fuel economy estimates that were within ±3 percent of the modeler's targets.

The actual simulation modeling results obtained for model baseline development and validation also assumed the implementation of idle-off engine technology on all six ICE vehicles. The modeling, thus, predicted increased fuel economy for the six vehicles (relative to the baseline simulation modeling results presented in Table F.15) as follows:

- Toyota Yaris, 43.3 CAFE mpg,
- Toyota Camry, 34.8 CAFE mpg,
- Chrysler 300, 27.4 CAFE mpg,
- Saturn Vue, 30.4 CAFE mpg,
- Dodge Grand Caravan, 25.2 CAFE mpg,
- Ford F-150, 18.6 CAFE mpg.

Three options were considered to develop a baseline scenario that did not include engine idle-off technology. One option was to "back out" an "average" idle-off technology effect to derive equivalent fuel economy in the absence of idle-off technology. A second option was to establish the vehicle-specific idle fueling rates that would be necessary to produce the official CAFE mpg values when idling was added to the idle-off technology simulations. A third option was to establish the vehicle-specific idle fueling rates that would be necessary to produce the simulated CAFE mpg values presented in Table F.15 when idling was added to the idle-off technology simulations.

Options two and three were evaluated first. Unfortunately, neither produced satisfactory results, as the required idle fueling rates, while reasonable in the aggregate, were inconsistent from vehicle to vehicle (e.g., the idle fueling rate for one four-cylinder vehicle might be twice that of another). Thus, option one was employed, but the average idle-off technology effect (expressed as percent change in fuel economy) was set at the average value derived during the evaluation of option two, which was equal to a 4.9 percent increase in fuel economy with idle-off technology. This resulted in displacement-consistent idle fueling rates ranging from 0.23 to 0.54 gallons per hour. Table F.16 presents the associated (adjusted) fuel economy estimates that were used for baseline ICE modeling for this project. As indicated, the estimates are quite reasonable relative to official 2009 CAFE data (generally within ±2 percent) with the exception of the F-150. However, the F-150 variation is not due to any weakness in the adjustment approach, but rather to the wide variation in the underlying simulation model results. Further modifications would have necessitated redoing the F-150 simulation modeling, which was beyond the scope of the work for this project. Since all scenario impacts are measured relative to the model baseline, the F-150 deviation is not considered to be a critical shortcoming, but all readers should recognize that the F-150 fuel economy impacts should be restricted to such a relative (to baseline) applicability.

Finally, as an integral component of the adjustment to the baseline simulation modeling data to remove the effects of idle-off engine technology, it was first necessary to account for the pre-adjustment distribution of energy losses within the vehicle engine. Idle losses were then simply added to the "no idle" losses to derive net driving cycle losses with idling. Cycle average engine gross thermal (indicated) efficiency was adjusted downward, based on the differential between average efficiency without idling and the reduced idling efficiency. Cycle average brake efficiency was then recalculated (relative to the value extracted from the simulation modeling results) by subtracting the parasitic losses (revised to include the effects of idling) from gross thermal energy and dividing by the cycle average fueling rate (also revised to include the effects of idling). Efficiencies "downstream" of the engine (i.e., torque converter and transmission efficiencies) were retained at the values extracted from the simulation modeling results. Tractive energy requirements are unaffected by idling, and the requirements estimated under step one of the two-step modeling approach employed for this project were within ±0.5 percent of the values extracted from the simulation modeling. The net result is a full accounting of the baseline ICE vehicle energy transfer (and losses), which was applied as the ICE baseline vehicle energy transfer map for the project. All project scenario impact data are evaluated relative to this baseline.

Hybrid Electric Vehicles

The energy transfer path for HEVs, as implemented for this project, includes all of the various components and energy loss mechanisms specified for ICE vehicles. Since the ICE vehicle model includes logic necessary to follow the energy transfer path through an electric machine (e-machine, generally consisting of a motor/generator, controller, and enhanced battery), no additional logic is required to model HEVs.[26] For convenience, a summary of the energy transfer pathways modeled for both ICE vehicles and HEVs is reproduced below in Table F.17.

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[26] The e-machine pathway is included in the ICE vehicle logic to allow users to model the effects of either braking energy or waste heat recovery. The presence of an e-machine on an ICE vehicle would blur the difference between ICE and HEV technology such that it is unlikely that an ICE would recover any large quantity of energy electrically (as would be implied by the presence of an e-machine) without also taking advantage of the other e-machine benefits of an HEV. Nevertheless, the e-machine pathway exists in the ICE processing logic, so no additional energy transfer logic is required to model HEVs. This is not meant to imply that HEVs would not offer additional energy efficiency benefits, simply that the mechanisms required to model such benefits are already present in the ICE vehicle logic.

TABLE F.16 Internal Combustion Engine Vehicle Modeling Baseline Fuel Economy Targets

Vehicle	Baseline Target CAFE mpg	Simulation Model CAFE mpg	Official 2009 CAFE mpg	Baseline Target Relative to Simulation (%)	Baseline Target Relative to Official (%)
Toyota Yaris	41.3	41.2	41.9	+0.2	−1.4
Toyota Camry	33.2	32.0	32.9	+3.8	+0.9
Chrysler 300	26.1	25.5	25.8	+2.4	+1.2
Saturn Vue	29.0	28.8	28.4	+0.7	+2.1
Dodge Grand Caravan	24.0	23.1	23.8	+3.9	+0.8
Ford F-150	17.7	17.6	19.6	+0.6	−9.7

TABLE F.17 Hybrid Electric Vehicle Energy Losses

Vehicle Component	Energy Loss Mechanism	Brief Description of Loss Mechanism
Internal combustion engine	Gross (indicated) efficiency	Energy lost in the thermal conversion of fuel energy to mechanical energy.
	Pumping losses	Energy used internally by the engine to move and compress air and move combustion products. These losses are subdivided into losses during periods of idling and non-idling.
	Friction losses	Energy used internally to overcome friction. These losses are subdivided into losses during periods of idling and non-idling.
	Braking losses	Energy consumed during periods of engine braking.
	Accessory losses	Energy used to power vehicle accessories.[a] These losses are subdivided into losses during periods of idling and non-idling.
Driveline	Torque converter losses	Losses due to all inefficiencies associated with the transfer of energy from the engine flywheel to the transmission.
	Transmission losses	Losses due to all inefficiencies associated with the transfer of energy from the torque converter to the wheels (including differential losses).
Electric machine	Vehicle braking recovery	Braking energy input into a driveline generator for storage and subsequent reuse (negative losses). It is assumed that recovered energy (if any) is “injected” into the driveline upstream of the torque converter and is thus subject to both e-machine and driveline losses.
	Waste heat recovery	Waste heat energy input into an electrical generator for storage and subsequent reuse (negative losses). It is assumed that recovered energy (if any) is “injected” into the driveline upstream of the torque converter and is thus subject to both e-machine and driveline losses.
	Generator losses	Energy lost in the conversion of mechanical braking energy to electrical energy.
	Battery storage losses	Energy lost in the conversion of electric energy to chemical energy.
	Battery discharge losses	Energy lost in the conversion of chemical energy to electric energy.
	Motor losses	Energy lost in the conversion of electrical energy to mechanical energy.

[a] For this project, this includes only accessories that are operational during the CAFE driving cycles.

As with ICE vehicles, a tailored HEV energy loss mechanism impact input format was developed to implement the model algorithms for this project. The specific format (and values for each modeled scenario) of the various data inputs are shown in the body of the report, but those inputs are structured as indicated in Table F.18. The HEV processing logic effectively "builds off" the logic for ICE vehicles, so that HEV modeling scenarios can generally be viewed as incremental to corresponding ICE efficiency scenarios.

Also as with ICE vehicles, not all (or even any) HEVs may have all of the components for which associated inputs are available. In such cases, the model is "instructed" to ignore these components, either by the input of an efficiency of 100 percent or the input of zero value energy capture. For example, a vehicle without a torque converter is simply modeled as through it has a 100 percent efficient torque converter, as a lossless component is no different (from an energy standpoint) than no component.

Since HEVs are treated as incremental to ICE vehicle technology, there are no baseline energy loss estimates established for HEVs. However, as part of the project, nominal energy loss impact estimates were established for HEV technology implemented on an advanced ICE platform. Examples of such advanced platforms are turbocharged gasoline direct injection (stoichiometric and lean burn), boosted and cooled exhaust gas recirculation, and Atkinson cycle technology.

The advanced technology distinction is important, since some of the benefits of HEV technology involve the ability to downsize or otherwise operate the vehicle engine in more efficient operating regions more often. To the extent that advanced ICE technology already allows more efficient engine operation, the benefit of hybridization will be reduced relative to the benefits that would accrue if a "non-advanced" ICE were hybridized. Thus, the nominal HEV benefits established for this project will underpredict the efficiency impacts of current generation HEVs relative to current generation ICE vehicles, and the HEV model established for this project should not be used to estimate the impacts of current HEVs without appropriate modifications to the nominal efficiency impacts.

It is also important to recognize that other important aspects of hybridization, including braking energy recovery and idle-off engine technology, are accounted for separately from any effects on engine operating efficiency. All effects can be modeled explicitly, but there is no fundamental distinction between an advanced ICE vehicle and an HEV with respect to each effect. The implementation of each component technology will move an ICE vehicle further along a "degree of hybridization" spectrum, but determining at what point an ICE vehicle becomes an HEV is subjective. For this reason, the modeling for this project does not attempt to define any particular set of HEV technology impacts as constituting an HEV, but rather allows the user to implement all of the various technologies enabled by hybridization, either individually or in combination, as desired.

The nominal hybridization impacts established for this project were validated using simulation modeling results for an advanced ICE platform and a corresponding P2 hybrid platform, both associated with the Toyota Camry (and both of which assume that idle-off engine technology is in place).[27] The effects were assumed to be constant (on a relative basis) across the other five vehicle platforms investigated in this project. Table F.19 summarizes the fuel economy data associated with the simulation modeling. The HEV model for this project was validated by running the nominal effects developed from the simulation modeling data through the model. The resulting fuel economy multipliers (HEV relative to ICE) ranged from 1.19-1.25, as compared to a simulation modeling impact for the Toyota Camry of 1.23. The variability range of −3 to +2 percent is due to differences in the distribution of energy losses between the baseline ICE engines used in the modeling for this project versus the Camry engine used in the HEV simulation modeling. Since individual losses are affected differently by hybridization, one would expect some difference in the predicted impacts of hybridization. Given the magnitude of the noted differences, it is believed that the HEV model performs quite satisfactorily (*against an advanced ICE vehicle baseline*).

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[27] NHTSA-EPA (2010b). *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025*. September 2010. Available at http://www.epa.gov/oms/climate/regulations/ldv-ghg-tar.pdf

TABLE F.18 Hybrid Electric Vehicle Input Parameters

Input Parameter	Application Methodology
Rolling resistance multiplier	Multiplier applied to the rolling resistance coefficients of the corresponding ICE scenario (allows for ICE/HEV differentials).
Aerodynamic drag multiplier	Multiplier applied to the aerodynamic drag coefficient of the corresponding ICE scenario (allows for ICE/HEV differentials).
Vehicle mass multiplier	Multiplier applied to the vehicle mass of the corresponding ICE scenario (allows for ICE/HEV differentials, affects both motive and rolling resistance forces).
Fraction of braking energy recovered	Represents the fraction of total braking energy that is input into an e-machine generator for subsequent consumption. It is assumed that energy output from the e-machine is “injected” into the drivetrain upstream of the vehicle transmission (and torque converter if present).[a]
E-machine generator efficiency[b]	Change in efficiency or losses.[c]
Battery storage efficiency[b]	Change in efficiency or losses.[c]
Battery discharge efficiency[b]	Change in efficiency or losses.[c]
E-machine motor efficiency[b]	Change in efficiency or losses.[c]
Transmission efficiency[b]	Change in efficiency or losses.[c]
Torque converter efficiency[b]	Change in efficiency or losses.[c]
Engine pumping loss improvement	Percentage reduction in losses.[c]
Engine friction loss improvement	Percentage reduction in losses.[c]
Cycle average accessory power	Compared to baseline ICE vehicle values to derive percentage reduction in baseline engine-driven accessory losses.
Engine braking loss improvement	Percentage reduction in losses.[c]
Additional idle loss improvement	Percentage reduction in idle losses, applied after the impacts of any pumping, friction, and accessory loss improvement.[c]
Gross thermal efficiency[b]	Change in indicated efficiency or losses.[c]
Fraction of combustion waste energy (heat) recovered	Represents the fraction of total combustion waste heat, both through coolant and exhaust, recovered. Any losses associated with the heat capture device itself should be explicitly accounted for in the specified fraction of energy captured. It is assumed that the capture device routes its output energy to an e-machine that subsequently “injects” its output energy into the driveline upstream of the vehicle transmission (and torque converter if present).[a]

[a] Must be greater than or equal to the fraction associated with the corresponding ICE vehicle scenario.

[b] The inputs are actually structured to allow the user to either: (1) enter a specified reduction in baseline vehicle component losses, (2) enter a specific efficiency, or (3) enter a specified percentage change in baseline vehicle component efficiency. Appropriate error checking is implemented to ensure that any specified percentage changes in efficiency do not increase efficiency above 100 percent.

[c] Relative to the corresponding ICE vehicle scenario.

TABLE F.19 Hybrid Electric Vehicle Simulation Modeling Results

Vehicle	Simulated Advanced ICE CAFE mpg	Simulated P2 Hybrid CAFE mpg	Camry Hybrid 2011 CAFE mpg[a]	Camry Non-Hybrid 2011 CAFE mpg[a]	Simulation P2 Relative to Advanced ICE	2011 Hybrid Relative to 2011Non-Hybrid
Toyota Camry	48.6	59.7	45.9	33.6	1.23	1.37
	Engine/Transmission Configuration				2011 impacts are 61% greater than advanced impacts	
	2.4 L AMT8	2.4 L AMT8	2.4 L AV	2.5 L A6		

[a] See http://www.fueleconomy.gov/feg/download.shtml, 2011 Datafile.

Battery (Only) Electric Vehicles[28,29]

The energy transfer path for BEVs, as implemented for this project, essentially consists of the e-machine and driveline component and energy loss mechanisms specified for HEVs, supplemented by the addition of losses associated with a battery recharger. CAFE testing requires that the battery state-of-charge for an electric vehicle (hybrid or battery-only) be the same both before and after testing, so battery-only CAFE explicitly includes battery charging losses. A summary of the energy transfer pathways modeled for BEVs is presented in Table F.20.

Because there are "extra" CAFE compliance credits available to producers of BEVs, it is important to understand how the CAFE fuel economy estimates that are modeled for BEVs in this project compare to the "creditable" fuel economy of such vehicles. U.S. CAFE rules adjust measured fuel economy for BEVs to determine a "creditable" fuel economy value that BEV manufacturers can use to determine their overall compliance with CAFE standards. As a result, there are actually two CAFE estimates for BEVs, one representing *measured* fuel economy and one representing *creditable* fuel economy.[30] The estimates produced for this project are consistent with *measured* CAFE fuel economy.

The difference between measured and creditable BEV CAFE fuel economy is determined through a series of factors that generally are intended to reflect: (1) differences in the offboard efficiency of electricity and petroleum production and distribution and (2) credits for reduced petroleum usage. The former is important because combustion inefficiency is one of the biggest energy losses associated with the thermal extraction of energy, and while this inefficiency occurs onboard an ICE vehicle, it occurs offboard at the electricity production source for a BEV. Thus, measured CAFE fuel economy inherently accounts for this inefficiency for ICE vehicles but entirely excludes the equivalent inefficiency of electricity production for BEVs. U.S. CAFE rules include post-measurement adjustments to correct for this difference.

There are three parameters that have been established to account for the upstream (i.e., offboard) differences between electricity and petroleum production and distribution. An electrical power generation efficiency factor, set at a "standard" value of 0.328 under U.S. CAFE rules, accounts for the combustion inefficiency of electricity production. An electrical power transmission efficiency factor, set at a "standard" value of 0.924 under U.S. CAFE rules, accounts for the inefficiency of moving electricity from the site of production to the battery recharging outlet. A petroleum refining and distribution efficiency factor, set at a "standard" value of 0.83 under U.S. CAFE rules, accounts for the inefficiency of upstream petroleum production and distribution. Combining these three factors yields an offboard equivalency factor of 0.365147 [0.328 × 0.924 × (1/0.83)], signifying that when offboard energy loss

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[28] Although in common use, it is perhaps informative for any readers not generally familiar with the terminology BEV to understand that it is not a "battery" per se that distinguishes BEVs (since HEVs also utilize an enhanced battery), but rather the fact that there is no onboard source of energy available to recharge the battery on a BEV. Because an e-machine is the only source of tractive energy on a BEV, battery capacity is generally enhanced relative to an HEV, but the more defining difference is that BEVs have no engine and rely entirely on offboard energy sources for recharging.

[29] The energy model has no explicit treatment for PHEVs, which are functionally equivalent to HEVs with some level of battery-only operational capability and an ability for offboard energy-based battery recharging. As such, a PHEV can generally be thought of as a vehicle that operates in either HEV mode or BEV mode. Accordingly, PHEV energy impacts are determined in this project through operating mode-weighted HEV and BEV impacts.

[30] There is a third regulatory fuel economy estimate, commonly known as the "adjusted" or "in-use" fuel economy estimate, that is designed to provide consumers with a more accurate estimate of the fuel economy they can expect to achieve during "real world" driving. While this estimate is based on measured CAFE fuel economy (as well as fuel economy measured through other supplemental testing), it is not a component of the CAFE program per se, is not used to determine compliance with CAFE requirements, and is thus not considered in the modeling performed for this project. These "in use" fuel economy estimates are displayed on a sticker affixed to the rear windows of new vehicles and compiled annually in a U.S. government publication known as the Fuel Economy Guide.

differences are considered, the "effective" CAFE fuel economy of a BEV is about 36.5 percent of its measured CAFE fuel economy. In other words, from an energy efficiency perspective, a BEV with a measured CAFE fuel economy of 100 miles per gasoline gallon equivalent (mpgge) is equivalent to an ICE (or HEV) with a measured CAFE fuel economy 36.5 mpgge.[31]

TABLE F.20 Battery (Only) Electric Vehicle Energy Losses

Vehicle Component	Energy Loss Mechanism	Brief Description of Loss Mechanism
Electric machine	Vehicle braking recovery	Braking energy input into a driveline generator for storage and subsequent reuse (negative losses). It is assumed that recovered energy (if any) is "injected" into the driveline upstream of the torque converter and is thus subject to both e-machine and driveline losses.
	Generator losses	Energy lost in the conversion of mechanical braking energy to electrical energy.
	Battery storage losses	Energy lost in the conversion of electric energy to chemical energy.
	Battery discharge losses	Energy lost in the conversion of chemical energy to electric energy.
	Motor losses	Energy lost in the conversion of electrical energy to mechanical energy.
	Accessory losses	Energy used to power vehicle accessories.[a]
Driveline	Torque converter losses	Losses due to all inefficiencies associated with the transfer of energy from the e-machine motor to the transmission. It is unlikely that any BEV will utilize torque converter technology. The technology remains "available" in the energy transfer path solely for "legacy" purposes. Torque converter technology is "removed" from the energy transfer path (and associated transfer losses are eliminated) by setting the torque converter efficiency to 100 percent.
	Transmission losses	Losses due to all inefficiencies associated with the transfer of energy from the e-machine motor (or torque converter) output to the wheels (including differential losses).
Battery charger	Charging losses	Energy lost in the transmission (and conversion) of electricity between an offboard electrical source and the e-machine battery. Battery storage losses are treated separately.

[a] For this project, this includes only accessories that are operational during the CAFE driving cycles.

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[31] All BEV fuel economy estimates for this project are reported as miles per gasoline gallon equivalent. Electricity is not generated, distributed, or sold on a volume basis, but the energy content of a gallon of gasoline can be used to determine how many "gallon equivalents" of electrical energy are consumed. For BEVs, a "standard" value of 33.705 kilowatt-hours per gallon (kW-hr/gal), as established under U.S. CAFE rules, is used to convert BEV energy consumption to gasoline gallon equivalents. For ICE vehicles, energy content is a measured parameter of CAFE testing, so values can deviate from the standard value used for official BEV CAFE testing. The BEV standard value of 33.705 kW-hr/gal is equivalent to 115,006 Btu per gallon.

There are also three parameters that apply to BEVs that address credits for non-petroleum usage. An alternative fueled vehicle credit, set at a “standard” value of 1/0.15 ($= 6.6\overline{6}$) under U.S. CAFE rules, accounts for the benefit of reducing petroleum-based fuel use.[32] A petroleum fuel accessory factor, set at a “standard” value of either 1.0 or 0.9, depending on whether an electric vehicle has no petroleum-fueled accessories or one or more petroleum-fueled accessories respectively. Finally, a driving pattern factor, set at a “standard” value of 1, is intended to correct any credits for differences in the utility of EVs. By setting the current value of this latter factor at 1, U.S. CAFE rules are explicitly assuming that there is no utility loss associated with EVs. For a vehicle with no petroleum accessories, the combined effect of these credit factors is $6.6\overline{6}$ [(1/0.15) × 1× 1], signifying that BEVs are eligible for non-petroleum credits equal to $6.6\overline{6}$ times offboard-adjusted fuel economy. In other words, from a CAFE credit perspective, a BEV with a measured CAFE fuel economy of 100 mpgge can be treated for CAFE compliance purposes as if it had a measured CAFE fuel economy of 243.4 mpgge [100 × 0.365147 × 6.666667]. In effect, once the offboard energy loss differential between electricity and petroleum production and distribution are considered, the net credit available to BEVs is about 2.434 times measured fuel economy [0.365147 × 6.666667].

By design, the fuel economy estimates developed for this project exclude any upstream effects. Such effects are explicitly considered in a separate portion of the project. To avoid any confusion, the CAFE fuel economy estimates also exclude any non-petroleum credits, instead representing measured CAFE fuel economy exclusively. If such estimates are to be used for evaluating the potential magnitude of future CAFE standards, both the standard upstream and non-petroleum credit factors should be applied to BEV fuel economy estimates, as such factors will be available to BEV manufacturers under current CAFE rules. In short, the BEV fuel economy estimates produced through the modeling for this project should be multiplied by 2.434 (unless otherwise indicated).

As with ICE vehicles and HEVs, a tailored BEV energy loss mechanism impact input format was developed to implement the model algorithms for this project. The specific format (and values for each modeled scenario) of the various data inputs are shown in the body of the report, but those inputs are structured as indicated in Table F.21. The BEV processing logic effectively “builds off” the vehicle load (mass, rolling resistance, and aerodynamic drag) logic for ICE vehicles and the e-machine logic for HEVs, so that BEV modeling scenarios can generally be viewed as incremental to corresponding ICE and HEV efficiency scenarios.[33]

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[32] This factor was originally derived for alcohol-based fuels, which typically were mixed with gasoline at a ratio of 85/15. Thus 1 gallon of the alcohol-based fuel would contain only 0.15 gallons of gasoline, so that mileage per physical *gasoline* gallon consumed (as distinguished from an energy-equivalent gallon) was 1/0.15, or about 6.67, times higher than the measured fuel economy for the alcohol-based fuel blend. This same factor has been carried over to all non-petroleum fuels, even though it is largely arbitrary from an engineering perspective.

[33] All of the e-machine components for BEVs will be of greater capacity than those of HEVs; the “incremental” logic construction is simply designed to ensure that BEV components are at least as efficient as those of HEVs. There is no attempt to imply that HEVs are somehow being “upgraded” to BEVs. The model treats BEVs and HEVs as separate and distinct entities, but carries HEV e-machine efficiencies forward (subject to change by the user) to ensure that BEV efficiencies are not unintentionally set at values lower than those for HEVs. The BEV load parameters are incremental to those of ICE vehicles rather than HEVs as there is no logical relationship between the load parameters of the three vehicle architectures. Thus, it is simpler to view BEV load effects (if any) as incremental to baseline ICE vehicle parameters, rather than tracking such parameters through an unrelated “middle” architecture.

TABLE F.21 Battery (Only) Electric Vehicle Input Parameters

Input Parameter	Application Methodology
Rolling resistance multiplier	Multiplier applied to the rolling resistance coefficients of the corresponding ICE scenario (allows for ICE/BEV differentials).
Aerodynamic drag multiplier	Multiplier applied to the aerodynamic drag coefficient of the corresponding ICE scenario (allows for ICE/BEV differentials).
Vehicle mass multiplier	Multiplier applied to the vehicle mass of the corresponding ICE scenario (allows for ICE/BEV differentials, affects both motive and rolling resistance forces).
Fraction of tractive energy dissipated through braking	Represents the fraction of tractive energy that is available for recovery (in the absence of regenerative braking). Braking losses are adjusted automatically for impacts associated with regenerative braking as well any changes to vehicle mass, rolling resistance, and aerodynamic drag parameters. Although the baseline ICE vehicles exhibit varying braking energy fractions (ranging from 19.9-26.2 percent), this variation results primarily from variations in the ICE operational characteristics. Since such variation should disappear along with the ICE in any movement toward BEV or FCEV technology, the nominal baseline braking energy fraction for all six BEV platforms was set to the average of the braking energy for the six ICE vehicle platforms (22.9 percent).
Fraction of braking energy recovered	Represents the fraction of total braking energy that is input into an e-machine generator for subsequent consumption. It is assumed that energy output from the e-machine is “injected” into the drivetrain upstream of the vehicle transmission (and torque converter if present).[a]
E-machine generator efficiency [b]	Change in efficiency or losses.[c]
Battery storage efficiency[b]	Change in efficiency or losses.[c]
Battery discharge efficiency[b]	Change in efficiency or losses.[c]
E-machine motor efficiency[b]	Change in efficiency or losses.[c]
Transmission efficiency[b]	Change in efficiency or losses.[c]
Torque converter efficiency[b]	Change in efficiency or losses.[c]
Battery charger efficiency	Efficiency. Energy lost in the transmission (and conversion) of electricity between an offboard electrical source and the e machine battery. Battery storage losses are treated separately (as indicated above).
Cycle average accessory power	Used to derive cycle average accessory load in kilowatts per hour per cycle mile.

[a] Must be greater than or equal to the fraction associated with the corresponding HEV vehicle scenario.
[b] The inputs are actually structured to allow the user to either: (1) enter a specified reduction in baseline vehicle component losses, (2) enter a specific efficiency, or (3) enter a specified percentage change in baseline vehicle component efficiency. Appropriate error checking is implemented to ensure that any specified percentage changes in efficiency do not increase efficiency above 100 percent.
[c] Relative to the corresponding HEV vehicle scenario.

Also, as with all other vehicle architectures, not all (or even any) BEVs may have all of the components for which associated inputs are available. In such cases, the model is “instructed” to ignore these components either by the input of an efficiency of 100 percent or the input of zero value energy capture. For example, a BEV without a torque converter (as should be true in virtually all cases) is simply modeled as through it has a 100 percent efficient torque converter, as a lossless component is no different (from an energy standpoint) than no component.

The nominal energy loss estimates established for BEVs are generally set at the values defined for the corresponding components in corresponding HEV evaluation scenarios. These nominal values can be considered baseline for practical purposes, although they are not intended to represent any particular existing BEV (for obvious reasons). More accurately, the nominal estimates are intended simply to guide users in the development of potential future energy loss estimates. It is fully expected that future BEV scenario estimates will differ from those implied by the nominal values, but it is not expected that they will signify less efficient components. Thus, the nominal values can best be viewed as implying suggested minimum efficiencies.

Despite the limited number of BEVs available for analysis today, the nominal baseline BEV data were validated using data available for the Nissan LEAF BEV. Tractive energy requirements for the LEAF over the CAFE driving cycles were estimated using the tractive energy model employed for this project, in conjunction with estimated rolling resistance, aerodynamic drag, and mass parameters for the LEAF, as reported by Nissan or available through the EPA's "Test Car" dataset.[34] Following the calculation of the tractive energy estimate, the nominal energy loss parameters established for current-generation BEVs were applied to derive an estimated CAFE fuel economy for the LEAF. The resulting fuel economy estimate of 140.5 mpgge differs from the official CAFE estimate for the LEAF of 141.7 mpgge by less than one percent. Thus, it is believed that the nominal energy loss estimates for BEVs are quite reasonable and that the performance of the BEV portion of the energy loss model is quite satisfactory.

Hydrogen Fuel Cell Electric Vehicles

The energy transfer path for FCEVs, as implemented for this project, consists of the e-machine and driveline component and energy loss mechanisms specified for BEVs, supplemented by the addition of losses associated with an onboard fuel cell system (stack plus balance of plant). Unlike BEVs, all battery recharge functions are performed by the onboard fuel cell system. A summary of the energy transfer pathways modeled for FCEVs is presented below in Table F.22.

Under United States Code Title 49 (Transportation), Subtitle VI (Motor Vehicle and Driver Programs), Part C (Information, Standards, and Requirements), Chapter 329 (Automobile Fuel Economy), Sections 32901 (Definitions) and 32905 (Manufacturing incentives for alternative fuel automobiles), hydrogen FCEVs are eligible for alternative fueled vehicle credits under the CAFE program. However, unlike BEVs, there are no formal procedures adopted under the CAFE program for standardizing FCEV CAFE measurements. To date, FCEV procedures are still developing and are, therefore, implemented under the Code of Federal Regulations, Title 40 (Protection of Environment), Chapter 1 (Environmental Protection Agency), Subchapter Q (Energy Policy), Part 600 (Fuel Economy and Carbon-Related Exhaust Emissions of Motor Vehicles), Subpart B (Fuel Economy Regulations for 1978 and Later Model Year Automobiles—Test Procedures), Section 600.111-08(f), which allows the EPA to utilize "special test procedures" under certain circumstances.

For this project, the same basic approach outlined above for estimating the CAFE fuel economy of BEVs was employed for FCEVs. This includes the same distinctions between *measured* and *creditable* fuel economy, with the estimates produced for this project representing *measured* CAFE fuel economy. Unlike BEVs, where the difference between measured and creditable CAFE fuel economy is determinable using "standard" factors codified in CAFE regulations, equivalent "standard" factors for FCEVs are yet to be codified. That is not to say that estimates for such parameters are unknown or otherwise impossible to develop, simply that no official estimates have been adopted.

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[34] The EPA's "Test Car" dataset is a dataset that contains data related to vehicle testing performed in compliance with U.S. emission standards and fuel economy requirements. The data is available by model year at http://www.epa.gov/otaq/tcldata.htm. For purposes of LEAF-based validation, data from the 2011 model year were utilized.

TABLE F.22 Fuel Cell Electric Vehicle Energy Losses

Vehicle Component	Energy Loss Mechanism	Brief Description of Loss Mechanism
Electric machine	Vehicle braking recovery	Braking energy input into a driveline generator for storage and subsequent reuse (negative losses). It is assumed that recovered energy (if any) is "injected" into the driveline upstream of the torque converter and is thus subject to both e-machine and driveline losses.
	Generator losses	Energy lost in the conversion of mechanical braking energy to electrical energy.
	Battery storage losses	Energy lost in the conversion of electric energy to chemical energy.
	Battery discharge losses	Energy lost in the conversion of chemical energy to electric energy.
	Motor losses	Energy lost in the conversion of electrical energy to mechanical energy.
	Accessory losses	Energy used to power vehicle accessories.[a]
Driveline	Torque converter losses	Losses due to all inefficiencies associated with the transfer of energy from the e-machine motor to the transmission. It is unlikely that any BEV will utilize torque converter technology. The technology remains "available" in the energy transfer path solely for "legacy" purposes. Torque converter technology is "removed" from the energy transfer path (and associated transfer losses are eliminated) by setting the torque converter efficiency to 100 percent.
	Transmission losses	Losses due to all inefficiencies associated with the transfer of energy from the e-machine motor (or torque converter) output to the wheels (including differential losses).
Fuel cell system	Hydrogen-to-electricity plus balance of plant losses	Energy lost in the conversion of hydrogen-based chemical energy to electricity, plus energy consumed internally (within the fuel cell system) to power balance of plant functions.

[a] For this project, this includes only accessories that are operational during the CAFE driving cycles.

Since the fuel economy estimates developed for this project are based on measured CAFE fuel economy, the lack of official standardized factors for adjusting measured CAFE poses no significant difficulty. However, readers should recognize that at some point, upstream adjustment factors relating the production and distribution of hydrogen to the production and distribution of gasoline are likely to be developed, and these factors, combined with FCEV credits for reduced petroleum usage, will dictate the difference between measured and creditable CAFE fuel economy. The credits for reduced petroleum usage will almost assuredly be the same as those for BEVs and all other alternative fueled vehicles, which, as described above, are represented by a measured fuel economy multiplier of 1/0.15 ($= 6.6\overline{6}$). But, until such time as the production and distribution equivalency factor is developed, the net measured fuel economy multiplier for FCEVs is unknown. Given that the explicit estimation of upstream energy efficiency is a separate component of this project, it should be possible to develop a project-specific estimate for this adjustment parameter, but that adjustment is not part of the modeling estimates discussed here. If fuel economy estimates are to be used for evaluating the potential magnitude of future CAFE standards, both upstream and non-petroleum credit factors should be applied to FCEV fuel economy estimates, as such factors will be available to FCEV manufacturers under current CAFE rules, albeit at currently undefined values.

Like BEVs, all FCEV fuel economy estimates for this project are reported as mile per gasoline gallon equivalent. Although the "standard" value of 33.705 kilowatt-hours per gasoline gallon (kW-hr/gal) established under U.S. CAFE rules to convert BEV energy consumption to gasoline gallon equivalents does not explicitly apply to FCEVs, there is no logical reason why the value would be altered for FCEVs (since it is a measure of gasoline energy content wholly independent of BEV and FCEV design). Thus, it is used without change for FCEV CAFE fuel economy calculations in this project. For comparative purposes, a value of 33.705 kW-hr/gal is equivalent to 115,006 Btu per gallon.

As with all other vehicle architectures evaluated, a tailored FCEV energy loss mechanism impact input format was developed to implement the model algorithms for this project. The specific format (and values for each modeled scenario) of the various data inputs are shown in the body of the report, but those inputs are structured as indicated in Table F.23. The FCEV processing logic effectively "builds off" the vehicle load (mass, rolling resistance, and aerodynamic drag) logic for ICE vehicles and the e-machine logic for BEVs, so that FCEV modeling scenarios can generally be viewed as incremental to corresponding ICE and BEV efficiency scenarios.[35]

Also as with all other vehicle architectures, not all (or even any) FCEVs may have all of the components for which associated inputs are available. In such cases, the model is "instructed" to ignore these components either by the input of an efficiency of 100 percent or the input of zero value energy capture. For example, an FCEV without a torque converter (as should be true in virtually all cases) is simply modeled as through it has a 100 percent efficient torque converter, as a lossless component is no different (from an energy standpoint) than no component.

The nominal energy loss estimates established for FCEVs are generally set at the values defined for the corresponding components in corresponding BEV evaluation scenarios. These nominal values can be considered baseline for practical purposes, although they are not intended to represent any particular existing FCEV (for obvious reasons). More accurately, the nominal estimates are intended simply to guide users in the development of potential future energy loss estimates. It is fully expected that future FCEV scenario estimates will differ from those implied by the nominal values, but it is not expected that they will signify less efficient components. Thus, the nominal values can best be viewed as implying suggested minimum efficiencies.

The nominal energy loss estimates for the two parameters that are unique to FCEVs—the fuel cell system efficiency and the battery loop share of non-recovered tractive energy—are developed through independent analysis of available data. Little data is available on the battery loop energy share. It is estimated that FCEV e-machines will be required to provide for a 3- to 5-mile battery-electric range during fuel cell system warm-up, as well as to supplement direct fuel cell energy during transient and peak power demands. To estimate the all-electric range implications, the tractive energy requirements of the first 3 and 5 miles of the CAFE city cycle were evaluated and compared to available recaptured braking energy (over the full city cycle), with the difference between these two measures indicating the amount of energy that must be returned to the battery by the fuel cell system. The CAFE highway cycle is excluded from the 3- to 5-mile analysis as it is a "hot start" cycle and therefore would not be affected by fuel cell warm-up issues.

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[35] It is likely that the e-machine components for FCEVs will be of differing capacity than those of BEVs. However, the "incremental" logic construction is simply designed to ensure that FCEV components are at least as efficient as those of BEVs. There is no attempt to imply that BEVs are somehow being "upgraded" to FCEVs. The model treats FCEVs and BEVs as separate and distinct entities, but carries BEV e-machine efficiencies forward (subject to change by the user) to ensure that FCEV efficiencies are not unintentionally set at values lower than those for BEVs. The FCEV load parameters are incremental to those of ICE vehicles rather than BEVs as there is no logical relationship between the load parameters of the three vehicle architectures. Thus, it is simpler to view FCEV load effects (if any) as incremental to baseline ICE vehicle parameters, rather than tracking such parameters through an unrelated "middle" architecture.

TABLE F.23 Fuel Cell Electric Vehicles Input Parameters

Input Parameter	Application Methodology
Rolling resistance multiplier	Multiplier applied to the rolling resistance coefficients of the corresponding ICE scenario (allows for ICE/FCEV differentials).
Aerodynamic drag multiplier	Multiplier applied to the aerodynamic drag coefficient of the corresponding ICE scenario (allows for ICE/FCEV differentials).
Vehicle mass multiplier	Multiplier applied to the vehicle mass of the corresponding ICE scenario (allows for ICE/FCEV differentials, affects both motive and rolling resistance forces).
Fraction of tractive energy dissipated through braking	Represents the fraction of tractive energy that is available for recovery (in the absence of regenerative braking). Braking losses are adjusted automatically for impacts associated with regenerative braking as well any changes to vehicle mass, rolling resistance, and aerodynamic drag parameters. Although the baseline ICE vehicles exhibit varying braking energy fractions (ranging from 19.9-26.2 percent), this variation results primarily from variations in the ICE operational characteristics. Since such variation should disappear along with the ICE in any movement toward BEV or FCEV technology, the nominal baseline braking energy fraction for all six FCEV platforms was set to the average of the braking energy for the six ICE vehicle platforms (22.9 percent).
Fraction of braking energy recovered	Represents the fraction of total braking energy that is input into an e-machine generator for subsequent consumption. It is assumed that energy output from the e-machine is “injected” into the drivetrain upstream of the vehicle transmission (and torque converter if present).[a]
E-machine generator efficiency[b]	Change in efficiency or losses.[c]
Battery storage efficiency[b]	Change in efficiency or losses.[c]
Battery discharge efficiency[b]	Change in efficiency or losses.[c]
E-machine motor efficiency[b]	Change in efficiency or losses.[c]
Transmission efficiency[b]	Change in efficiency or losses.[c]
Torque converter efficiency[b]	Change in efficiency or losses.[c]
Fuel cell system efficiency	Efficiency. Energy lost in the conversion of hydrogen-based chemical energy to electricity plus energy consumed internally (within the fuel cell system) to power balance of plant functions).
Battery loop energy share[d]	Represents the fraction of tractive energy required (after the independent consideration of recovered braking energy) to be routed from the fuel cell system through the battery and e-machine motor. The balance of tractive energy (after the independent consideration of recovered braking energy) is assumed to be routed from the fuel cell directly to the e-machine motor.
Cycle average accessory power	Used to derive cycle average accessory load in kW-hr per cycle mile.

[a] Must be greater than or equal to the fraction associated with the corresponding BEV vehicle scenario.
[b] The inputs are actually structured to allow the user to either (1) enter a specified reduction in baseline vehicle component losses, (2) enter a specific efficiency, or (3) enter a specified percentage change in baseline vehicle component efficiency. Appropriate error checking is implemented to ensure that any specified percentage changes in efficiency do not increase efficiency above 100 percent.
[c] Relative to the corresponding BEV vehicle scenario.
[d] Excluding regenerative braking energy, which is routed entirely through the e-machine generator battery motor energy transfer loop.

The transient and peak power battery demands were estimated by comparing HEV battery operations to HEV engine operations (as the HEV battery is also used to supplement an engine that is undersized relative to peak power demand). Since HEV battery sizing is economically biased toward smaller battery capacity (as ICE displacement is more economical than battery capacity), while FCEV battery sizing will likely be economically biased toward larger battery capacity (as fuel cell capacity is less economical than battery capacity), the HEV battery energy demand share was increased by 20 percent to estimate potential FCEV demand share. The resulting demand shares were then combined with the all-electric warm-up period estimates to produce an estimated overall battery loop energy share of 25 percent for a 3-mile all-electric start and 33 percent for a 5-mile all-electric start.[36]

Current fuel cell system efficiencies generally appear to range from 50-55 percent. To select a specific nominal value for current systems, as well as validate all other nominal values for FCEV componentry, the FCEV model employed for this project was used to estimate CAFE fuel economy for the current Honda FCX and Mercedes F-Cell fuel cell vehicles. The tractive energy requirements for both vehicles over the CAFE driving cycles were estimated using the tractive energy model employed for this project, in conjunction with estimated rolling resistance, aerodynamic drag, and mass parameters for the two vehicles as reported by Honda and Mercedes, or available through the EPA's "Test Car" dataset.[37] Following the calculation of the tractive energy estimate, the nominal energy loss parameters established for current-generation FCEVs were applied to derive estimated CAFE fuel economy. Since the nominal fuel cell system efficiency was not precisely defined at this point, the efficiency required to *exactly* match the reported CAFE fuel economy for each vehicle was determined.

For the FCX, a fuel cell system efficiency of 54.2 percent was required to match reported CAFE fuel economy. For the F-Cell, the corresponding efficiency was 49.7 percent. Both are quite consistent with expected efficiencies in the range of 50-55 percent, so it is believed that the nominal energy loss parameters established for FCEVs are quite reasonable. For purposes of this project, the nominal current-generation fuel cell system efficiency was set at 53 percent, a bit higher than the midpoint (52 percent) of the inferred FCX and F-Cell system efficiencies to ensure that effects of future improvements are not overestimated relative to current systems. Applying a 53 percent fuel cell system efficiency to the FCX and F-Cell results in a 2.2 percent underprediction of FCX CAFE fuel economy (84.8 versus 86.8 mpgge) and a 6.6 percent overestimation of F-Cell CAFE fuel economy (81.3 versus 76.3 mpgge).[38] Based on this validation, it is believed that the nominal energy loss estimates for FCEVs are quite reasonable and that the performance of the FCEV portion of the energy loss model is quite satisfactory.

F.2.3 Summary of the Modeling "Performance Cycle"

To ensure the equivalent performance capability of vehicles modeled under each of the scenarios evaluated for this project, a supplemental "performance cycle" was evaluated (in addition to the two CAFE driving cycles upon which the basic work for this project is focused). Unlike the CAFE driving cycles, the performance cycle is not defined by fixed time and velocity characteristics, but rather varies for each of the six baseline vehicle platforms evaluated in the project (see above for a description of the six platforms). In effect, the performance cycle is a manufactured cycle designed to estimate the peak

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[36] These are the combined cycle averages. The CAFE city cycle indicated a battery loop energy share of 45 percent for a 3-mile all-electric warm-up period and 60 percent for a 5-mile all-electric warm-up period. The corresponding shares for the CAFE highway cycle were 1.5 and zero percent.

[37] The EPA's "Test Car" dataset is a dataset that contains data related to vehicle testing performed in compliance with U.S. emission standards and fuel economy requirements. The data is available by model year at http://www.epa.gov/otaq/tcldata.htm. For purposes of FCX and F-Cell validation, data from the 2011 model year were utilized.

[38] Hydrogen fuel cell CAFE fuel economy values are reported in units of miles per kilogram (mi/kg) of hydrogen. Although a kilogram of hydrogen is roughly equivalent on an energy basis to a gallon of gasoline, the mi/kg data were converted to equivalent miles per gasoline gallon equivalent, as follows. The energy content of hydrogen was taken as 120 MJ/kg, which equals $33.3\overline{3}$ kWh/kg. Taking the standard gasoline energy content of gasoline as 33.705 kWh/gal, as established for BEV CAFE testing procedures, yields a factor of 1.01115 (= $33.705/33.3\overline{3}$) kilogram per gasoline gallon equivalent. Although the effect is small (1.1 percent change), reported miles per kilogram fuel cell vehicle fuel economies were adjusted accordingly.

power required to achieve published 0-60 acceleration times for the evaluated vehicles. Once established for a baseline vehicle platform, the identical performance cycle is run for all of the scenarios and alternative vehicle architectures that correspond to that baseline to establish the peak power required to execute the cycle (defined for this project as the equivalent performance power).

The published 0-60 acceleration times for the baseline vehicle platforms defines the time characteristic of the performance cycle for each vehicle. The velocity characteristic is set in accordance with the derived relation:

$$v = [a \times (t/t_{0\text{-}60})] + [b \times (t/t_{0\text{-}60})^2] + [c \times (t/t_{0\text{-}60})^3] + d$$

where

v = the driving cycle velocity at time “t” (in miles per hour),
t = the driving cycle second,
$t_{0\text{-}60}$ = the 0-60 acceleration time (in seconds),
a = a regression coefficient = +73.2122338111447 (t=19.9),
b = a regression coefficient = -17.5373517702585 (t=-5.3),
c = a regression coefficient = 0, and
d = the regression intercept = +4.26569962371015 (t=5.2),

While precise acceleration curves for individual vehicles can vary (and can be modeled in detail by simulation models using component technology definitions), the modeling approach employed in this project is based on more aggregated energy losses and is unable to predict technology-specific variations in acceleration curve shape. To adapt the modeling approach employed in this project to an evaluation of constant-performance engine (or alternative power source) output requirements, a generalized acceleration curve was developed using published 0-60 acceleration times.[39] Figure F.4 graphically depicts the data used to develop the generalized curve as well as the shape of the resulting curve for three distinct 0-60 mph acceleration times (6, 8, and 10 seconds). The actual curves employed in this project are be specific to the 0-60 mph acceleration times for each of the six vehicle platforms evaluated, and these times are held constant across all evaluated scenarios (and architectures) to estimate the engine (or alternative power source) output required to achieve identical 0-60 mph performance.

There are, of course, a large number of acceleration curves available for individual vehicles. For this project, two curves were analyzed to derive the generalized relation: one curve for a relatively slowly accelerating vehicle (10.3 second 0-60 mph time) and one curve for a relatively quickly accelerating vehicle (6.1 second 0-60 mph time).[40] These two curves span the range of 0-60 mph acceleration times associated with the six vehicle platforms evaluated in this project. The specific acceleration data for the two curves were generalized by expressing the time associated with each time/velocity data point as the fraction of total 0-60 mph time. For example, a data point indicating the vehicle velocity at a time of two seconds would be expressed as 2/6.1 (or 0.328) for the 6.1 second 0-60 mph curve, signifying the velocity at 32.8 percent of the total acceleration time. This effectively creates a dataset that is independent of any given 0-60 mph time, and can thus be used to investigate whether a reliable generalized curve can be developed. The resulting data were aggregated and subjected to regression analysis to derive the

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[39] Both the variation and generalization being discussed here refer to the *shape* of the acceleration curve, not absolute acceleration rates. For example, a vehicle that accelerates at X mph per second at velocity zero might accelerate at 0.98X mph per second after a given velocity interval. It is the definition of vehicle-specific aspects of this acceleration “decay” function that is beyond the scope of the model employed in this project. Individual vehicle acceleration rates estimated under the approach employed in this project *will* properly vary in accordance with published 0-60 times and the *shape* of the developed (generalized) acceleration curve.

[40] The specific data are for the 2006 Honda Civic Hybrid (10.3 seconds) and the 2006 Toyota Camry SE V6 (6.1 seconds). The data were downloaded from http://www.roadandtrack.com/tests/data-panel-archive (using the link labeled “2006 Toyota Camry SE V6,” which contains data for both vehicles).

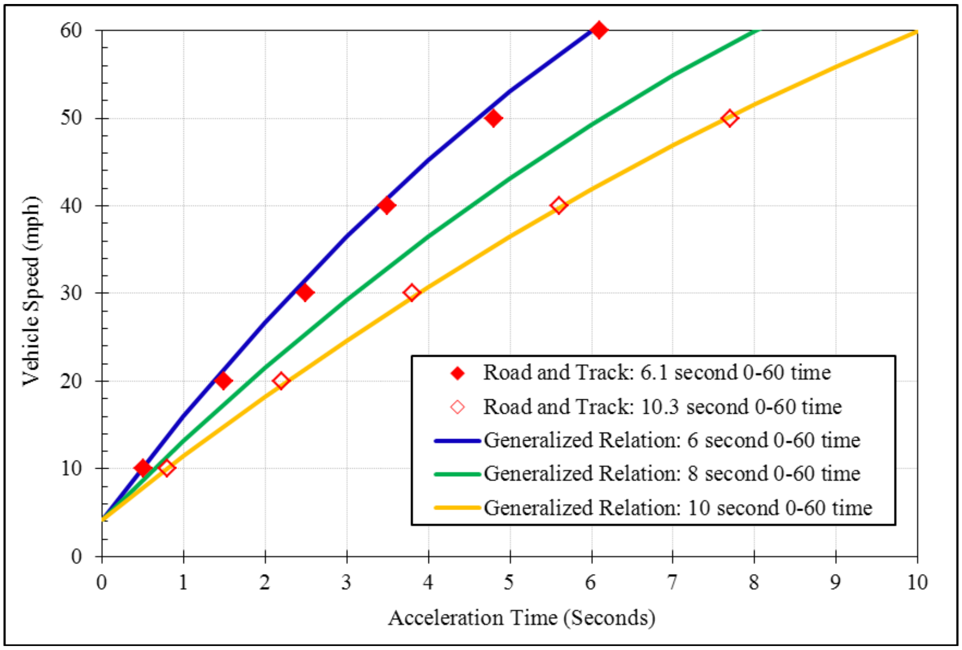

FIGURE F.4 Generalized wide-open-throttle acceleration curve.

generalized relation presented above (and graphically depicted for three specific 0-60 mph times in Figure F.4). As indicated there, the fit is quite good (the actual r^2 for the analysis is 0.997), implying that any error resulting from the use of a generalized acceleration curve is small relative to actual vehicle-specific acceleration decay functions.[41]

Using the generalized acceleration decay curve function, tractive energy requirements can be estimated over the performance cycle in exactly the same manner as described above above for the CAFE cycles. Estimated tractive energy required during each second of the performance cycle is equivalent to the power required during that second.[42] The maximum power estimated over the performance cycle is an indicator of the peak power required at the wheels. Peak power at the wheels is then converted into peak required engine (or alternative energy source) power in exactly the same manner as described above for the “second step” of the CAFE fuel economy modeling process employed for this project. This allows for a reasonable estimation of the engine (or alternative power source) peak output required to achieve the same level of vehicle performance as observed for baseline ICE vehicles.

Table F.24 presents a summary of the baseline performance data and associated performance cycle estimates for the six baseline vehicle platforms evaluated in this project. As indicated, the performance cycle power estimates are generally within ±6 percent of rated power, with the exception of the Chrysler 300, which differs by 10 percent. Since neither the reported 0-60 mph times nor the performance cycle power estimates are precise, the specific source of “error” is unknown. However, given the relative imprecision of the estimation approach employed, the level of estimation accuracy is

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[41] Note that the “fit” depicted in Figure F.4 is actually not precise, since the 6.1 second regression data are plotted relative to a 6 second generalized curve, and the 10.3 second regression data are plotted relative to a 10 second generalized curve. Nevertheless, the fit of the data to the generalized curves is sufficiently evident that the only marginally different generalized 6.1 and 10.3 second curves are omitted for clarity.

[42] For example, power (P) in watts is equal to energy (E) in newton-meters per unit time in seconds. If we evaluate energy requirements at a frequency of 1 hertz (i.e., once per second), then P = (E / seconds) × 1 second = E.

TABLE F.24 Vehicle Performance Data

Performance Parameter	Toyota Yaris	Toyota Camry	Chrysler 300	Saturn Vue	Grand Caravan	Ford F-150
0-60 mph Time (seconds)	10.7	8.8	6.9	10.4	9.3	7.7
Engine Rated Power (hp)	106	158	250	169	205	300
Performance Cycle Peak Power (hp)	101.7	163.5	224.9	159.2	193.2	314.2
Performance Cycle Power Deviation	−4.1%	+3.4%	−10.0%	−5.8%	−5.8%	+4.7%

quite good. In all cases, the predicted performance cycle power is calibrated to match the rated power of each vehicle platform engine, and all alternative scenario and vehicle architecture estimates are evaluated on a *relative* basis only, so that all unbiased estimation error will “cancel out” in across-scenario comparisons.

F.3 BATTERY VEHICLES

Electric vehicles have been around since the 19th century and originally were more popular than gasoline vehicles. Electric vehicles were much easier to start and did not require shifting gears, which was difficult with the transmissions of the time. However, EVs were slow, had very limited range, and required electrical power to recharge, restricting their use mainly to cities. Sales peaked in 1912 as the technology of gasoline vehicles and fuel improved.[43] In recent years, interest in EVs has greatly increased, because they can operate in part or wholly without petroleum-based fuels, and because they emit no pollutants at the point of use.

Electric vehicle battery packs consist of two main components: the battery cells and the battery management system (BMS) that controls the operations of the cells and interfaces with the vehicle electronics. Cells are likely to cost about two-thirds of the cost of the pack, while the BMS plus structural components and assembly will account for the remainder. Battery cells are discussed first and the BMS later in this section.

F.3.1 Hybrid and Electric Vehicles

Two types of vehicles use externally charged batteries for propulsion: PHEVs and BEVs. Each has a rechargeable battery designed for a specific service.

PHEVs such as the Chevrolet Volt (also called an extended-range electric vehicle) have an electric motor powered by a lithium-ion (Li-ion) battery coupled to a gasoline-powered generator. They also have a conventional lead acid battery to start the gasoline engine and power accessories. When the Li-ion battery is depleted, the gasoline engine starts and charges the battery, which continues to power the car to give a greatly extended range. The engine is not used to power the car directly. The Volt has a range of about 35-40 miles on battery power alone and 375 miles total before refueling. The Li-ion battery has storage capacity of 16 kWh, which can be recharged by plugging the car into an electrical outlet. With a conventional household 120 volt (V) outlet, the battery can be fully recharged in about 10 hours. A 240 V outlet can charge it in about 4 hours. The battery is warranted for 8 years and 100,000 miles, but its capacity is expected to deteriorate by about 20 percent over the warranty period. The Volt currently costs about $39,000, about $16,000 more than a well-equipped Chevrolet Cruze, a similar

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[43] See http://en.wikipedia.org/wiki/History_of_the_electric_vehicle. Accessed March 2012.

conventional car.[44] The cost to manufacture the battery cells, the price to General Motors, and the cost of assembling the battery pack are all proprietary, but the total cost is reported to be about $8,000 ($500/kWh).[45] This cost is consistent with battery prices for the Tesla model S BEV, introduced in 2012. That model offers three battery options: 40 kWh for the base, 60 kWh for an additional $10,000 ($500/kWh for the upgrade), and 85 kWh for another $10,000 ($400/kWh).[46]

An alternative configuration, such as the Toyota Prius plug-in, has the same parallel electrical/mechanical drive configuration as the current Prius HEV but a much larger battery (although smaller than the Volt-type PHEV). The Prius PHEV should be able to drive 10-15 miles on the battery alone. The engine can drive the wheels as well as charge the battery.

The Nissan Leaf is an example of all-electric propulsion. It is powered by a 24 kWh Li-ion battery and has a range of about 100 miles. The Leaf can be charged from a household 120 V outlet, but a 240 V charging port is recommended to reduce the time required. The Leaf is connected to the port with a special outlet and plug developed by the Society of Automotive Engineers and agreed to by all manufacturers. The Leaf battery pack costs about $12,000 ($500/kWh).[47]

Other manufacturers are planning to introduce EVs of both types over the next several years. Improvements in battery technology will be critical to the success of EVs.

F.3.2 Batteries for Plug-In Hybrid and Electric Vehicles

Lead acid batteries have been the dominant technology for starting engines and powering accessories for a century. As the only available technology, they were used in attempts to revive EVs in the 1990s, but they proved inadequate. Nickel-metal hydride (Ni-MH) batteries with better energy storage capabilities were developed and used successfully in the first generations of HEVs. They have excellent high rate capability and long cycle life, are very robust, and can withstand abuse conditions without damage. However, Ni-MH batteries are also too heavy and bulky for the greater energy demands of PHEVs and BEVs.

Table F.25 summarizes the energy storage capability of the principal vehicle battery systems. While the Li-ion battery has higher energy density, it costs more than the lead acid batteries, because it uses more expensive materials. Unlike lead acid, the term Li-ion does not define a unique system. New materials, such as silicon-Li alloy anode and layered Ni-Co-Mn oxide cathode materials with higher energy density are under development, as are new cathode materials, although they may cost more and are unproven in vehicle operation.

There is general agreement that the Li-ion battery will be the battery of choice for EVs. It was developed specifically for the portable electronics industry 20 years ago because of its light weight, superior energy storage capability, and long cycle life—attributes that also are important for EVs. Cell performance has increased steadily with improvements in the internal electrode structure and cell design and manufacturing processes, as well as the introduction of higher-performance anode and cathode materials. Evolution of the technology is shown in Figure F.5.

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[44] See http://www.chevrolet.com/volt-electric-car/. Accessed February 2012.

[45] H. Takeshita, Tutorials at the 28th and 16th International Power Sources Seminars, The International Battery Seminar, LLC, Boca Raton, Fla., March 2011.

[46] See http://www.teslamotors.com/models/options. Accessed March 2012. Note that costs are not the same as prices, which may include markups and/or subsidies.

[47] Press release, Nissan press Release 2011 DOE Annual Merit Review May 9-13, 2011, presentation.

TABLE F.25 Typical Cell Characteristics in 2010

System	Wh/l	Wh/g	$/h	Comments
Lead acid	80	25	0.05	Reliable, low cost Battery for the EV1
Ni-MH	430	90-100	0.35	Hybrid battery of choice Replacement by Li-ion likely
Li-ion	570	203	0.20	Graphite anode, lithium cobalt oxide cathode, $LiPF_6$ organic solvent electrolyte

SOURCE: T.B. Reddy, ed., *Lindens Handbook of Batteries,* McGraw Hill, 2011.

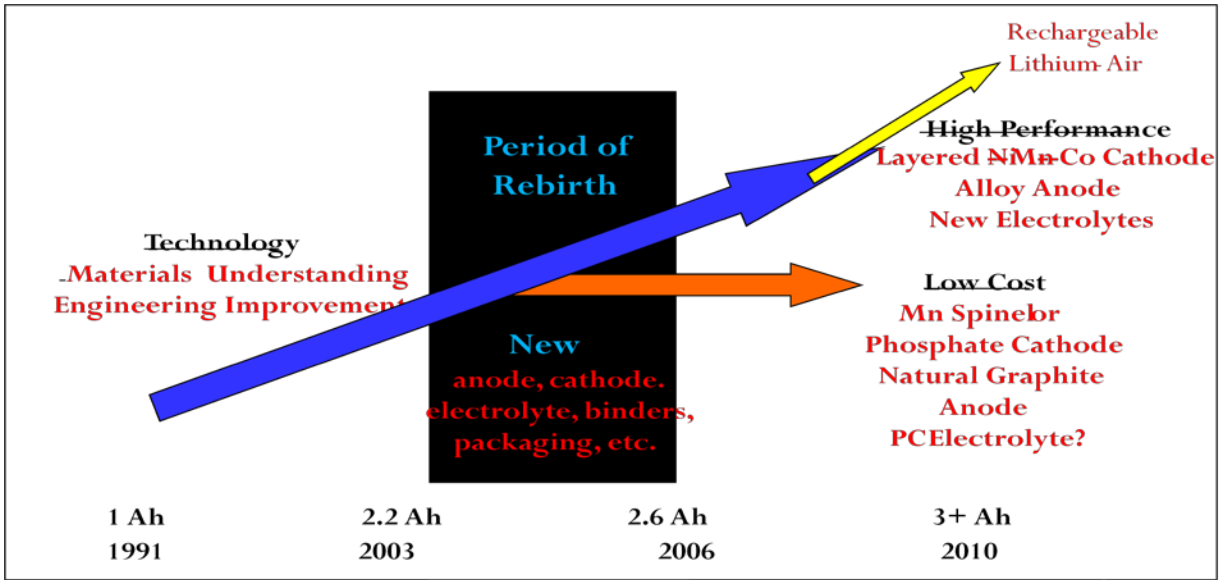

FIGURE F.5 Improved performance of lithium-ion 18650 cells.

The 18650 cell is typical example of the Li-ion technology. It is a cylinder 18 mm in diameter and 65 mm high, somewhat smaller than the size of a standard D battery. Originally, a lithium cobalt oxide cathode and a hard carbon lithium intercalation anode produced 3.6 V open circuit voltage. In 1991, the cost of the 18650 was $3.17/Wh. Twenty years later in 2010, the same cell cost $0.20/Wh, while the capacity of the cell had increased from 1 Amp-hour (Ah) to over 3 Ah in the same volume. These improvements resulted from the introduction of new, high-performance materials, improvements to the cell and electrode structure design, and high-volume production processes with reduced wastage. As a rule of thumb for highly automated cell production, cell materials constitute about 80 percent of the cost of the cell.[48] During the period 1991-2010, production increased from about 30 million to over 9 billion cells annually. After 20 years, designs, manufacturing processes, and economies of scale had matured, and costs have leveled out. In the time period 2004-2005, new anode and cathode materials were introduced to continue the growth in energy storage capability. The DOE battery research and

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[48] As used here, “materials” means processed materials ready for cell manufacture. It does not mean raw materials, which may be much cheaper. The processing of these materials is subject to considerable cost reduction, as is the cell manufacture.

development (R&D) programs are expected to result in a steadily increasing performance and materials. In the outer years, new battery chemistries, such as lithium-air, would significantly increase performance and the range between the need for recharging.

This pattern of cost reduction is typical for high-volume battery cell production. Cells for vehicles are likely to be prismatic (flat plate) or pouch-type rather than cylindrical, because these are easier to cool and arrange in stacks. The production process for flat plate cells differs from that for cylindrical cells, but it is anticipated that the cost will follow a similar learning pattern as the 18650 cell. An initial high cost is expected to be followed by cost reductions from improved production efficiency in cells and materials as the process matures.

The newer higher performance cathode, anode, electrolyte, and separator materials under development today are more expensive but should follow the same learning curve for cost reduction as for the original graphite anode and cobalt cathode, electrolyte, and separator materials as the processes are refined and electrode design parameters are understood.

Unlike lead acid batteries, which all use the same set of chemicals for the anode and cathode, many different chemistries are used to construct Li-ion cells, as shown in Table F.26. Thus, it is necessary when discussing the Li-ion system to keep in mind the composition of the anode and cathode active materials.

Each cell chemistry has its own unique characteristics of chemistry, particle size, reactivity, safe operating envelope, etc., that must be adapted to the production process. Several different chemistries may be used as HEVs, PHEVs, and BEVs emphasize different characteristics in their batteries. The choice of the active materials and cell design determine its energy storage capability. The total available energy in a battery is governed by thermodynamics of the electrode reactions. Thinner, high surface area electrodes are preferred for efficient usage of the active materials, but result in lower energy storage (Wh/cc and Wh/kg). Thicker electrodes offer higher Wh/kg and Wh/cc, but result in a lower efficiency of material usage at the high current demands of PHEV and BEVs. The life of the battery is limited by the volume expansion-contraction of the anode and cathode materials during charge and discharge, leading to loss of contact with the current collector in the electrode structure. The battery pack assembly of the individual cells requires sophisticated control circuitry to protect the pack from rogue cells that could disrupt normal operation. Battery pack design and assembly is discussed below.

In selecting cells for the battery pack, a trade-off is often made between higher voltage and higher capacity cell technology (such as nickel cobalt aluminum or layered manganese nickel cathode) versus lower capacity but lower cost (such as the lithium manganese spinel or lithium iron phosphate based technology with longer cycle life). Both the Volt and Leaf employ the manganese spinel cathode and graphite anode in a flat-plate configuration with $LiPF_6$ electrolyte for long cycle life and relatively low cost.

F.3.3 Automotive Battery Packs

The battery pack for vehicles consists of two main components (1) an assembly of cells to meet the design requirements for total energy (kWh) and voltage and (2) a BMS to control its operation. A typical pack might consist of several hundred cells configured in series strings to achieve the design voltage, with sufficient strings in parallel to achieve the design energy. Cells represent 50-70 percent of the cost of battery packs. The BMS plus structural components and assembly are responsible for the rest.

The safe operating parameters for each type of cell must be established, and the BMS must be designed to maintain the cells within those parameters for long life and safe operation of the battery. The goal of 10 to 15 years service for automotive applications is far longer than for use in electronic devices and approaches that required for avionic applications. The BMS senses the temperature, current flow, and voltage of each individual cell in the pack. Depending on the particular company’s design, the BMS can isolate an individual cell that deviates from prescribed limits to prevent damage to the battery. It also controls the cooling system required to prevent overheating of the cells during charging or discharging.

TABLE F.26 Characteristics of Lithium-Ion Batteries Involving Different Chemistries

	Cathode/Anode			
Characteristics	Nickel Cobalt Aluminum Oxide/ Graphite	Manganese Spinel/Graphite	Iron Phosphate/ Graphite	Manganese Spinel/Lithium Titanium Oxide
Durability	Good	Fair	Good	TBD
Power	Fair	Fair	Good	Good
Energy	Good	Good	Fair	Poor
Safety and abuse tolerance	Poor; safety concerns	Fair	Good	Good
Cell voltage	3.6	3.8	3.3	2.5
Some battery developers	Johnson Controls/Saft	LG Chem Ltd.	A123	EnerDel
Associated vehicle manufacturers	Toyota/Ford	GM	Daimler HEV buses	

NOTE: Cathode chemistries are frequently referred to as involving a spinel crystal structure. Actually there are no pure spinel structures present in Li-ion batteries; spinel-like would be more accurate.
SOURCE: *Transitions to Alternative Transportation Technologies; Plug-in Hybrid Electric Vehicles.* The National Academies Press, Washington, D.C. 2010. Available at http://www.nap.edu/catalog.php?record_id=12826.

Cooling can be by air or liquid. The latter is more expensive but maintains better thermal control, which may be important for longer cell life. Adequate cooling is particular important if the battery is being charged rapidly in hot weather because a significant amount of heat is generated within the pack.

It is commonly understood that a cell internal fault (e.g., short) is a “single-point-fault” type such as occurs in a cell separator failure, allowing the anode to contact directly the cathode creating an internal short in a single cell. Since all cells in the pack are a part of the circuit, the entire energy stored in the battery pack can be released in that single shorted cell, with the potential for critical results. It has long been accepted that you cannot just reduce the likelihood of a single-point-fault to the level necessary to provide the needed safety; nor can one verify that a single-point-fault “just will not happen.” However, with the energy-density demands of the automotive market and the use of large-format cells, it is not realistic to expect to optimize energy-density without having the possibility of a cell internal fault propagating.

The BMS enhances cell/battery safety by sensing the on-set of failure, then taking swift action for mitigation. The BMS monitors the battery and individual cells for anomalous behavior in real-time including cell voltage, cell external temperature, battery temperature, battery current, and cell balancing history. This includes rapid fault detection of cell shorting; e.g., a cell voltage “spike” and actions to isolate the fault. The BMS operates at speeds capable of accurately capturing the highest frequency effects. In effect there are three major components that characterize the safety of a battery pack: the failure rate of an individual cell, the probability of propagation of a single cell fault to the pack, and the failure rate of the electronics.

The intent is to identify impending problems and take action to mitigate accordingly, i.e., predictive mitigation. The BMS reaction time is less than 2.5 milliseconds. The BMS restricts operation of the battery to within the “operational envelope.”

In order to deduce the internal cell concentration and temperature profiles, an understanding of the cell (cell model) and an understanding of the cell operational history is required; e.g., recent charging/discharging profiles. It has also been observed that existing safety mechanisms for cells used in consumer electronics, such as the positive temperature coefficient devices can be of little value in large format cells. More importantly, it has been observed that current interrupt devices (CIDs) for the 18650 cell can be too slow to mitigate a problem in large-format cells where the temperature increase can fully develop in some areas of the cell before the CID can react.

The propagation of an internal short induced within a single cell depends on the history of the cells in the pack as well as the immediate operating conditions. Battery temperature, cell internal temperature profile, and cell state-of-charge play a key role in holding the battery/cells within a desired "operational envelope" such that it is quantifiably less probable that a cell internal short leads to propagation. The best solution builds on understanding the bounding criteria associated with whether an internal short will or will not propagate.

Safety analysis can have both qualitative and quantitative components. Both aspects are meaningful in understanding assurance of system safety. In military and commercial aerospace, both components are fundamental to the safety analysis process. The BMS consists of programmable sensors, intelligence, communications, self-diagnosis, status reporting, and control mechanisms. Each battery block is designed to protect itself. Single-point faults are fundamentally disallowed in commercial aerospace critical systems. This is a typical requirement for any scenario where safety criticality is an issue, such as in aviation. The single-point-fault issue has a long history, including tragic events that have often been traced back to such a root cause. Exceptions to this exclusion rule are exceedingly rare.

F.3.4 Battery Technology for Future Applications

Strong research programs in national laboratories, universities, and private industry are developing new materials, lowering costs, and improving the energy storage capability of the battery. All of the components—anode, cathode, separator and electrolyte—are included in these studies. For instance, the experimental programs to develop silicon to replace graphite in the anode may significantly improve capacity. The new layered nickel-manganese-cobalt oxide materials, now under development, offer similar improvements in cathode performance but will require sophisticated production processes. These materials will be more expensive at the start but can be expected to show significant cost reduction as demand increases. In volume production, cathode materials using nickel and cobalt may have resource limitations that could result in price increases eventually.

F.3.4.1 Forecast for Cost of Electric Vehicle Batteries 2012 to 2030

Future costs of Li-ion cells for vehicles are likely to follow the trajectory of cells for electronic applications. Those costs fell in a regular manner for 10 years and then began to level off as production processes matured and improved in reliability. This is typical for a learning curve in manufacturing of batteries as the cell internal designs and production process becomes stabilized. Materials suppliers should have a similar learning curve as increased demand for materials for cell construction lead to improvements in their production. As the best battery chemistries for vehicle applications are established, and cell design and production capability is established within the United States, costs will come down rapidly at first and then more slowly. Costs of the battery pack (in addition to the cells) also should decline at about the same rate as cells as manufacturers and suppliers improve designs and production techniques.

In 2010, the United States had essentially no Li-ion cell manufacturing capability or infrastructure to support it. All cells for battery packs have been imported from Japan, Korea, or China. U.S. volume production of automotive batteries is just beginning. By 2030, cells and battery packs could become an important industry here if the manufacturing capability and supporting infrastructure are established over the next decade or two. Infrastructure in parts, materials, and trained engineers to support the industry will

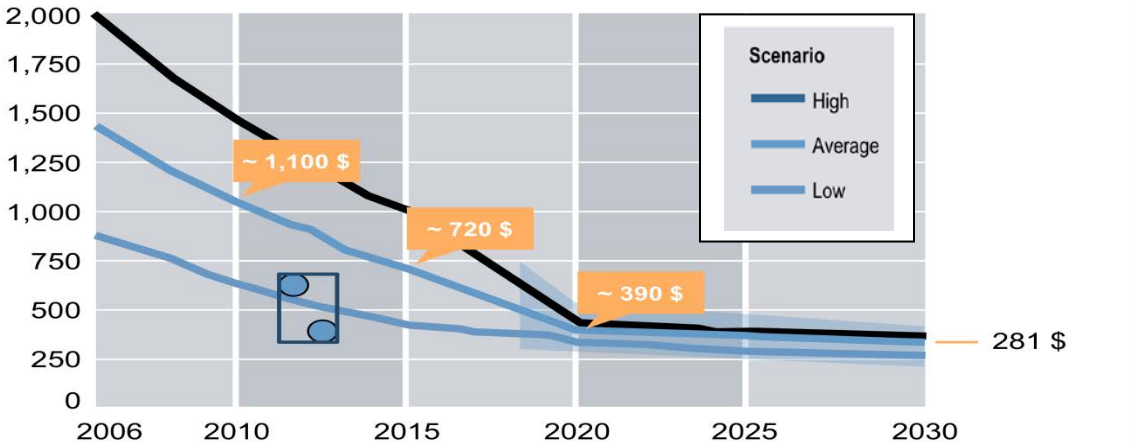

FIGURE F.6 Estimated cost ($/kWh) of lithium-ion automotive propulsion batteries for the period 2010 to 2030.

be required. A battery recycling effort will be needed when large numbers of battery packs reach the end of their useful lifetimes. Recycling works well for lead acid batteries, almost all of which are returned, and the components are used in construction of new batteries.

The projected costs in Figure F.6 start with the 2012 pack costs assumed for the Chevrolet Volt and Nissan Leaf at $0.50/Wh (or $500/kWh). The assumption is made that the cost of cells manufactured in the United States for vehicle application will decline, but not as rapidly as the Li-ion cells for electronic applications did in their early years. The cost of those cells declined more than 95 percent in 20 years. In addition, the costs of assembling the cells into packs will decline, but perhaps not as rapidly as the cells. Midrange BEV pack costs are estimated at $250/kWh (45 percent reduction from $450 in 2010). Optimistically, pack costs might reach $200/kWh (55 percent reduction). PHEV pack costs are likely to be $60/kWh to $70/kWh higher.

The production process for flat cell production is simpler than for cylindrical cell production yet requires greater precision. As production of vehicle batteries gets underway, the production process will be improved going down the learning curve for the production process for vehicle cells, as was the case for cells for electronic applications.

In 2010, mature cylindrical cell production had a defect rate of 1 in 5 million cells, based on incidents of battery failure. All of these incidents have been traced to a manufacturing defect, not a chemistry issue. As a result, safety can be expected to improve as the production process for vehicle batteries matures.

DOE has funded an intense effort to develop new higher-performance materials that lead to increased driving range on a single charge. Although cells made using the new materials give higher energy storage capability, they also increase the cost if nickel and cobalt are major components of the materials. It is expected that, with time, the cells made with new materials will undergo the same decrease in cost related to volume production. While the new materials are initially more expensive, they should follow the same learning curve with appropriate lowering in cost.

A car built as a BEV today that gets 30 mpg would require about 26 kWh/100 miles, or 260 Wh/mile. For a range of 300 miles, the battery would have to be at least 78 kWh. While not impossible (see the mention of the Tesla above), this would be prohibitively expensive, heavy, and bulky for most applications and would take prohibitively long to charge. It is difficult to envision how a Li-ion battery that large could be developed that would be feasible for general use. More advanced technologies, such as lithium-air with about 5210 Wh/kg, could be developed for automotive applications in this period, but, even if successful, they probably will not be widely available until after 2030. If new battery technologies are not commercialized, the only alternative to achieve such a range would be to design smaller, lighter cars. If the energy demand can be reduced to about 17 kWh/100 miles, as per the efficiency measures discussed above, and if battery pack costs are reduced to $200/kWh, then longer distance travel would become more practical, in particular if batteries can be developed to withstand repeated fast charges. Otherwise, BEVs will be limited mainly to short distance travel in urban and suburban areas.

PHEV batteries are smaller than those for BEVs, so the pack cost per kilowatt-hour is somewhat higher. The optimistic estimate for 2030 is $260/kWh and the midrange is $300/kWh.

F.3.4.2 Estimation of Battery Costs in 2030 to 2050

Li-ion batteries will continue to improve after 2030 but probably at a reduced rate. Strong R&D programs are developing new cathode and anode materials, electrolytes, and separator materials, which are expected to reach maturity and yield dividends in this time period. New active materials with higher energy content, such as silicon alloy anodes and layered nickel-manganese-cobalt materials, should become available in volume production. Materials account for about 80 percent of the cost of Li-ion cells in high-volume production. Hence, cost reduction will largely focus on materials used to produce the cells. In addition, the DOE program to support the electric vehicle application can be expected to deliver higher-performance materials that potentially will lower costs. The practical cost limit of Li-ion cells is probably about $80/kWh, and the corresponding pack cost would be $150-$160/kWh.[49]

As R&D improvements continue with government support, new high-energy materials and new electrolytes are being developed. This may led to next-generation technologies such as high-energy lithium-sulfur and lithium-air systems using a fuel cell oxygen cathode and lithium metal anode. Another long-term option is the flow cell, such as the semi-solid lithium rechargeable flow battery.[50] At this writing, these systems are still in an advanced research stage but not commercialized.

The lithium-air, in particular, has received significant attention. Lithium metal has the highest voltage and capacity of any anode material, and oxygen in aqueous electrolyte is an excellent low-cost catalyst with good performance. A significant effort is underway to develop the system into a commercial product. Most approaches use a ceramic barrier between the two electrodes to prevent water from reaching the lithium metal anode. Although the challenge is difficult, significant progress has been made. However, the committee does not believe that the chances of commercial success of any of these advanced batteries are high enough to warrant inclusion in its scenarios.

While the exact route to low-cost cells and batteries is not clear, it should be possible to reach a cost of $160/kWh in 2050 for automotive propulsion cells. Figure F.7 shows a possible cost trajectory. An optimistic projection is $150/kWh. Only with volume manufacturing of the battery cells, electrolyte separator, and cathode materials will these cost targets be met. PHEV batteries are estimated to be about $40/kWh higher.

All of the cell materials can be used for multiple applications. If the goal of $150/kWh can be met for automotive use, then electronic cells should have the same cost structure. In addition, they should benefit from increased reliability. Defect-free, uniform cell-to-cell output with 10^{-8} reliability will be required for automotive batteries to meet reliability and safety requirements—significantly higher than what is required for electronic cells.

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[49] ARPA-E's BEEST Program: Ultra-High Energy, Low Cost Energy Storage for Ubiquitous Electric Vehicles, presentation to the committee by David Danielson, Program Director, ARPA-E, March 21, 2011.

[50] Dudata, M., et al., Semi-Solid Lithium Rechargeable Flow Battery, Advanced Energy Materials, Vol. 1, Issue 4, July 2011.

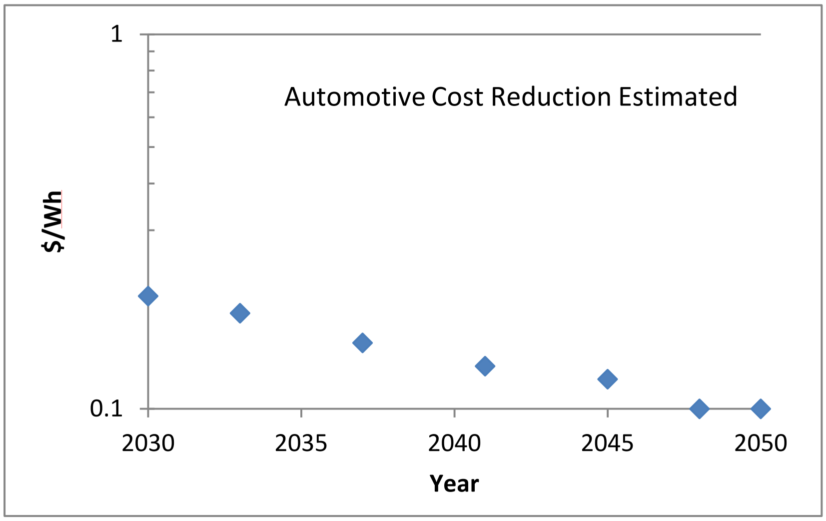

FIGURE F.7 Cost for automotive batteries in the time period 2030 to 2050.

F.3.5 Barriers to the Widespread Adoption of Electric Vehicles

The main problems facing the use of EVs are:

1. The high cost of the battery,
2. The lower driving range relating to the fundamental lower energy storage capability of the battery compared to gasoline,
3. Improving the durability and longevity of the batteries,
4. Ensuring safety, and
5. Establishing a domestic vehicle battery industry.

Solving all these issues simultaneously will be difficult.

F.3.5.1 Battery Cost

Battery cost is a key issue for the success of the electric vehicle. Lower cost electrode materials will be an important step. Cathode, separator, and electrolyte are the main contributors to the cell cost. Most of the new cathode materials are composed of high-cost nickel and cobalt materials. However, there are lower cost, lower performance materials such as lithium iron phosphate and manganese spinel cathode coupled with graphite anode materials that can be made for about $10/kg or less in large volume. Even with low-cost materials, there is a learning curve for manufacturing that progressively lowers cost, based on identifying slow and costly processes and improving on them.

Economy in manufacturing requires automated production capability to achieve repeatability and uniform capacity cell-to-cell, essential for safe operation in automotive applications and a long life requirement. The new cell designs are prismatic, not cylindrical as for the electronic applications, and have a different production process than the cylindrical electronic cells. The process is somewhat simpler but requires greater emphasis on process control and lower cost materials.

There has been no U.S. production of Li-ion automotive cells until recently with the opening of the A123 facility in Michigan. Li-ion cells are produced in Asia, where a trained workforce exists, and imported for assembly into packs in the United States. There is no infrastructure for materials components or a skilled workforce base in the United States, and these must be re-established for the U.S. industry to become viable. This is a significant barrier to overcome. It takes at least 5 years for a production line to become fully operational. It takes a similar period to train a workforce. Overall, it will take 5 to 8 years and significant capital investment to re-establish this infrastructure, but it is essential for a viable Li-ion battery industry capable of competing in the world market.

F.3.5.2 Battery Performance

Battery performance must be improved if BEVs are to widely replace ICE vehicles. The present average auto has a range of about 300 miles on a tank of gasoline. Very few affordable BEVs will greatly exceed 100 miles for the next several years. That will be adequate for some drivers for some applications, but many people will not be willing to accept that limitation. Lighter, more efficient vehicles will be developed, extending the range or lowering the size and cost of the battery for the same range, but it will also be important to squeeze more performance out of batteries without compromising cost. If the range most EVs can travel without lengthy recharging is no more than 100 miles, they will be limited largely to local travel in an urban or suburban environment.

F.3.5.3 Durability and Longevity

Durability and longevity are functions of both design and manufacturing precision. Exchange current is the fundamental rate at which electrode reactions function in a reversible manner. Higher currents stress the reaction on both charge and discharge and often cause formation of unwanted and possibly damaging changes in the reaction mechanism. For instance, forcing the graphite negative to recharge quickly can result in lithium depositing on the surface rather than entering into the lattice. This lithium metal reacts directly with the electrolyte, depositing unwanted reaction byproducts that block the surface and increasing the current density at other parts of the electrode, permanently damaging cell operation. Thus, rapid charging and discharging can shorten the lifetime of the cell.

Poorly designed porous electrode structures can lead to lower performance. The mixture of conductive diluent, binder, and active material should result in a uniform reaction throughout the electrode structure. Any blockage in the porosity reduces the ability to deliver high-current pulses and lowers the capacity of the electrode.

Volume changes during charge and discharge introduce stress inside, with movement of electrodes in cylindrical cells. Cell design for long life must accommodate the volume change in present cell materials. Low-cost phosphate and spinel materials have a minimum volume change but have low energy content. The volume change introduces stress inside the cell and can limit cycle life.

F.3.5.4 Safety

Safety of the battery is a critical issue. The recent Volt fires, although not a result of operational failures, are a reminder that the safety questions must be addressed. There is no long-term experience with commercial automotive batteries. For the 18650 size Li-ion cell used in electronic applications, the failure rate is about 1 in 5 million cells, some of which led to laptop computer fires. All incidents have been traced to manufacturing defects. This rate is not acceptable for automotive applications, and significant efforts must be made to improve the production processes to produce a higher quality cell in keeping with established failure rate of 10^{-8}.

Li-ion cells are highly energetic and contain sufficient energy to heat the cell to more than 500°C if released rapidly inside the cell. That could cause neighboring cells to also fail, leading to a catastrophic event. The failure rate for Li-ion 18650 cells equates to a reliability rate of about 99.9999 percent. This level of reliability is not satisfactory for electric vehicle batteries where 99.999999 percent is the minimum required.[51] Therefore, it is essential that cell construction defects in the individual cells, as well as defects in the battery pack itself, are eliminated so that a catastrophic event "will not happen." Testing is required to prove that the battery will meet the standard.

One additional potential barrier may also deter drivers from buying BEVs is future reliability of the electrical grid. As discussed in Chapter 3, the grid has been very reliable and will be capable of charging many millions of EVs if charging is done at night. However, outages of days and weeks are possible. Under such conditions, BEVs could be unavailable (PHEVs could still operate). Fast charging by many people at the same time, i.e., on returning from work, will place an additional strain on the grid system as well, possibly leading to increased vulnerability of the grid.

F.3.6 Electric Motors

Essentially all HEVs, PHEVs, and EVs use rare-earth-based interior permanent magnet (IPM) motors. These rare earth magnets were invented and produced initially at General Motors Research Laboratories, which developed and patented a high-flux magnet material using rare earth materials termed "MagnaQuench" for neodymium-iron-boron (NdFeB). These magnets have almost an order of magnitude greater flux than other types of permanent magnets and created a revolution for many products that needed small high-flux magnets, including speakers, hard drives, etc.

There were significant price reductions after the MagnaQuench patent expired in the 1990s. The production of rare-earth magnets then moved from the United States to Japan. In 2000, China lowered rare-earth prices to levels that others could not match. Finished magnets were selling for less than $16 per kilogram. China ended up with a market share of more than 90 percent and, effectively, a monopoly on rare-earth-magnet materials. In 2008, China raised the price of rare-earth magnet materials and has steadily increased the price, reaching as high as $60/kg. An automotive traction motor uses 1 to 1.5 kg of rare-earth-magnet materials, which strongly influences the cost of motors for EVs. The rare-earth alloys are also used in the hydrogen-absorbing cathode in the Ni-MH battery used in electronics and in hybrid vehicles.

IPM motors are by far the most popular choice for hybrid and EVs because of their high power density, specific power, and constant power-speed ratio (CPSR). Performance of these motors is optimized when the strongest possible magnets (e.g., NdFeB) are used. Cost and power density (power density criterion translates to torque density and acceleration) are emerging as the two most important properties of motors for traction drives in hybrid and EVs, although high efficiency and specific power are essential as well.

China has the largest rare-earth resources in the world and currently controls the supply of rare-earth-materials mining and processing. Whereas China previously supplied rare-earth metals to other countries for magnet production, it recently vertically integrated to include magnet and motor production, instead of exporting the rare earth ore. China also announced its intention to limit exports on rare-earth materials in order to ensure a supply for their own needs, and it has used its control of rare earths as a foreign policy tool. There is always the distinct possibility that a limited supply and/or very high cost of rare-earth magnets could make these materials unavailable and/or too expensive outside China.

Rare-earth mines in the United States were shut down in about 2000. The United States produced rare earth materials mainly from the Molycorp Mountain Pass mine in California. Recently, MolyCorp announced that the Mountain Pass mine, which has a significant reserve of rare earth ores, is being reactivated. However, restarting mining operations will require a significant capital investment and time. Once in operation, the Mountain Pass mine could supply the rare earth needs of North America for a decade or more. Molycorp also announced finding significant new deposits near its mine in California.

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[51] H. Takeshita, Tutorials at the 28th and 16th International Power Sources Seminars, The International Battery Seminar, LLC, Boca Raton, Fla.

The potential shortage of rare earths has driven DOE to examine the role of permanent magnets in electric machines and technologies that could either eliminate or reduce the need for rare-earth magnets. The DOE strategy involves three parallel paths:

1. If there is a reasonable chance that rare earth magnets will continue to be available, either from sources outside China or from increased production in China, then development of IPM motors using rare earth magnets should be continued with emphasis on meeting the cost target.
2. Since there is a possibility that rare earth magnets may become unavailable or too expensive, the effort to develop new designs for permanent magnet motors that do not use rare earth magnets needs to be continued. Other possible magnet materials include samarium-cobalt, Alnico, and ferrites. Alternatively, efforts to develop motors that do not use permanent magnets but offer attributes similar to IPM motors are encouraged.
3. New magnet materials using new alloys or processing techniques that would be less expensive or have comparable or superior properties to existing materials should be developed if possible.

Recently Toyota announced that it has developed a new material that has equivalent or superior capability in as a substitute for the rare earth materials in electric motors for its line of EVs (Reuters, 2012) (5). Toyota could bring the technology to market in 2 years if the price of rare earths does not come down. Toyota has developed an induction motor that is lighter and more efficient than the magnet type motor now used in the Prius and does not use rare earth materials. The present Prius has more than 20 pounds of rare earth materials.

For the past several years, the IPM motor has been considered the obvious choice for electric traction drive systems. However, with the rapidly increasing costs of magnets and the possibility of a future shortage of rare-earth metals, the use of IPM motors would not be economical or technically feasible.

Surface-mounted permanent magnet motors have relatively high specific power but restricted CPSR. The speed of these motors is limited due to challenges of magnet retention. Essentially, they have no advantage over IPM motors. Induction motors have lower power density compared with IPM motors but also cost less. They are robust and have a medium CPSR. Being a mature technology, they are reliable but have little opportunity for improvement. Most manufacturers consider induction motors the first choice if IPM motors are not available.

Switched reluctance (SR) motors are durable and low cost, and they contain no magnets. Their efficiency is slightly lower than that of IPM motors at the “sweet spot,” but the flatter profile of SR motors can give higher efficiency over a typical drive cycle. The torque density of SR motors is much better than that of induction motors. They require different power electronics compared to IPM motors. Significant concerns about SR motors are torque ripple and acoustic noise. Efforts are currently being directed to solve those problems through rotor design, modified electronics, and stiffening of the housing.

For the past several years, the IPM motor has been considered the obvious choice for electric traction drive systems. However, with the rapidly increasing costs of magnets and the possibility of a future shortage of rare-earth metals, the use of IPM motors may not continue to be economically or technically feasible. Table F.27 estimates the future costs of electric motors, assuming such shortages do not occur.

TABLE F.27 Projected Fixed and Variable Cost Coefficients for the Motor System

	HEV/PHEV		BEV/FCEV	
	Fixed	Variable/kW	Fixed	Variable/kW
Midrange case–US $				
2010 baseline	$668	$11.58	$668	$11.58
2015 average of 2010 and 2020	$586	$10.38	$586	$10.38
2020 $4%/2% electronic/other	$504	$9.18	$504	$9.18
2025 average of 2020 and 2030	$449	$7.74	$464	$8.24
2030 1% learning+motor integration	$393	$6.30	$425	$7.30
2035 1% learning	$374	$5.99	$404	$6.95
2040 1% learning	$356	$5.70	$384	$6.60
2045 1% learning	$338	$5.42	$365	$6.28
2050 1% learning	$322	$5.15	$347	$5.97
Optimistic case–US $				
2010 baseline	$668	$11.58	$668	$11.58
2015 average of 2010 and 2020	$586	$10.38	$586	$10.38
2020 $4%/2% electronic/other	$504	$9.18	$504	$9.18
2025 average of 2020 and 2030	$427	$7.34	$442	$7.84
2030 1% learning+motor integration	$349	$5.50	$381	$6.50
2035 1% learning	$332	$5.23	$362	$6.18
2040 1% learning	$316	$4.97	$344	$5.88
2045 1% learning	$301	$4.73	$327	$5.59
2050 1% learning	$286	$4.50	$311	$5.32

F.3.7 Cost and Performance Evolution of a Battery Electric Vehicle

A complete shift to battery propulsion eliminates the ICE drivetrain and its inefficiencies (and costs), although the new electrical components—and especially the battery—are expensive and are not without inefficiencies. However, the committee foresees that all components of the BEV drivetrain—and especially the battery—will improve in performance (e.g., achieve higher energy and power density) and achieve significant cost reductions over the 2010-2050 period. Battery costs are the key factor in electric vehicle cost effectiveness. Although projections of future battery costs are quite uncertain, the committee believes these costs, approximately $500/kWh in 2010, can be reduced to $200-$250/kWh by 2030 and $150-$160/kWh by 2050 (Table F.28). In addition, the combination of increasing efficiency of the electric drivetrain, the substantial decreases in vehicle loads, and the expected increase in the allowable battery depth of discharge (about 80 percent in 2010, 90-94 percent by 2050) reduce the amount of battery capacity needed to achieve a fixed range. For example, the battery capacity needed to attain about 100 miles in on-road capacity for a Camry-sized car is about 38 kWh in 2010 but shrinks to 16 kWh (optimistic) to 20 kWh (mid-level) by 2050 in the two scenarios examined. If EV performance and cost follow the path shown in Table F.28, the cost penalty of a 100-mile range EV compared to a conventional drivetrain vehicle will shrink from its current level of about $16,000 to $2,000-$3,000 by 2030, and the EV will become the less expensive than its conventional counterpart by 2050. In addition, the gasoline-equivalent fuel economy of such a vehicle—already high at about 150 mpg (EPA test) in 2010—can rise to 195-225 mpg by 2030 and 250-300 mpg by 2050.

TABLE F.28 Details of the Potential Evolution of a Midsize Battery Electric Vehicle, 2010-2050

	2010	2030 mid	2030 opt	2050 mid	2050 opt
Test cycle range, miles	130	130	130	130	130
Electric motor power, kW	110.8	91.6	85.6	81	71.2
Fraction of braking energy recovered, %		87.5	90.2	92.5	94
Electric motor efficiency, %		90.7	91.6	92.5	93.5
Net battery charge efficiency, %		86.7	87.8	88	
Accessory demand, W into generator	152	104.1	98.2	92.3	84.6
Battery depth of discharge, %	80	88	92	90	94
Battery capacity, kWh	37.6	25.8	21.7	19.9	15.9
Fuel economy, test mpg_e	152	195	225	250	303
Fuel economy, test kWh/100 mile	22.1	17.3	15	13.5	11.1
Battery cost, $/kWh	450	250	200	160	150
Incremental cost versus baseline, $	15,979	5,401	4,384	3,184	2,050
Incremental cost versus conventional, $	15,979	2,968	2,139	−475	−1,353

F.4 HYDROGEN FUEL CELL ELECTRIC VEHICLES

F.4.1 Hydrogen Fuel Cell Electric Vehicles in 2010

F.4.1.1 Fuel Cell Powertrain

A typical FCEV powertrain schematic is shown in Figure F.8. As in hybrid vehicles, a battery in FCEVs enables regenerative braking and supplements the fuel cell system in meeting transient on-road power demands (including start up). It thereby enables the fuel cell to be sized for nominal driving requirements and efficient operation. This battery is larger than those currently used in HEVs, because it must power driving for 2-5 miles while the fuel cell warms up in cold weather. It is recharged from the fuel cell directly and through regenerative braking. Future improvements in the performance and cost of HEV batteries will apply to FCEVs as well.

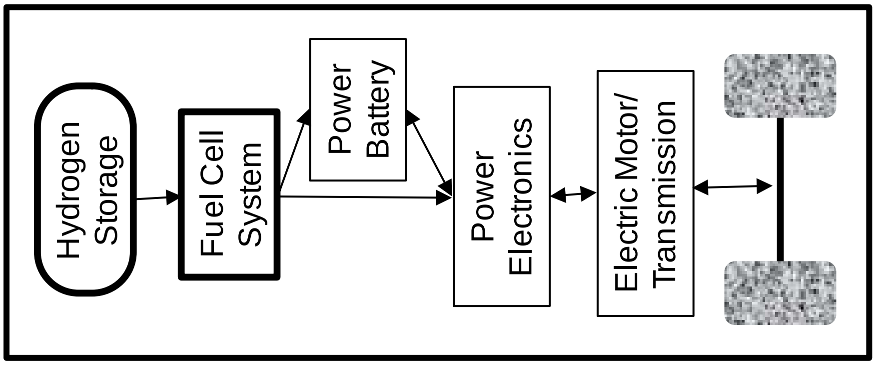

FIGURE F.8 Typical FCEV powertrain schematic.

Over the past decade, FCEVs in demonstration fleets have shown significant technology advances toward commercial readiness in the areas of performance and cost. For example (James et al., 2010; EPA, DOT, CARB, 2010; Carlson et al., 2005; Kromer and Heywood, 2007; Bandivadekar et al., 2008), the cost of automotive fuel cell systems has been reduced from $275/kW in 2002 to $51/kW in 2010 (based on projections of high-volume manufacturing costs); on-road vehicle durability has doubled since 2006 to 2,500 hours (equivalent to approximately 75,000 mile range); and vehicle range has increased to at least 300 miles. Vehicles have demonstrated the capability to meet all urban and freeway driving demands. The remaining advancement under development is high load driving at high ambient temperatures.

F.4.1.2 Fuel Cell Systems

Fuel cell stacks currently used in automotive applications are based on the polymer-electrolyte membrane/proton-exchange membrane (PEM). PEMs operate at moderate temperatures that can be achieved quickly so they are suitable for the infrequent and transient usage of on-road automotive service. Structured catalysts using precious metals as the active catalytic materials (primarily platinum) convert hydrogen gas and air into internal carriers of electric charge at the anode and cathode, respectively. A separation membrane transports hydrogen ions from the anode to the cathode. Improvements in stack durability, specific power, and cost have resulted from methods to improve the stability of the active catalytic surface area and from new membrane materials and structures. For example, stack lifetimes of 1,000-2,500 operating hours have been demonstrated in on-road vehicles, and short-stack laboratory tests with newer membrane technologies have demonstrated (using accelerated test protocols) over 7,000 hours. In addition, improvements in stack durability and efficiency have resulted from continued reduction of stack mass transport losses due to improved hydrogen and air flow management and membrane hydration management and improved efficiency and durability of electrode structures.

The balance of plant (BOP) consists primarily of mature technologies for flow management of fluids and heat. Significant improvements in efficiency and cost result from continuing simplifications in BOP design.

Further reductions in the cost of fuel cell systems are expected to result from downsizing associated with improved stack efficiency and improved response to load transients. Significant additional cost reductions will result if vehicle loads (weight, rolling resistance, and aerodynamics) are reduced, because that will allow the use of smaller hydrogen tanks and fuel cells with lower total power.

F.4.1.3 Fuel Cell System Efficiency: 2010.

Fuel cell system efficiency measured for representative FCEVs driven on chassis dynamometers at several steady-state points of operation has shown a range of first-generation net system efficiencies from 51 to 58 percent (Wipke et al., 2010a, b). Second-generation vehicle systems have shown 53 to 59 percent efficiency at one-quarter rated power, as illustrated in Figure F.9. System efficiency has improved slightly while the major design changes have focused instead on improving durability, freeze performance, and cost (Wipke et al., 2010a, b).

With current fuel cell system efficiencies, fuel storage capacity and vehicle attributes (weight, aerodynamics, and rolling resistance), FCEVs are currently capable of 200-300 miles driving range and fuel efficiency over twice that of the comparable conventional ICEV. Examples include the 20 mpg 2007 Chevrolet Equinox, which, when equipped as an FCEV, achieved 45 mi/kg-H_2 (1 kg of H_2 is the energy equivalent of 1 gallon of gasoline). Similarly, the 2011 Honda Clarity FCEV achieves more than 60 miles/kg-H_2, but an equivalent ICEV would have gotten only 27 mpg.

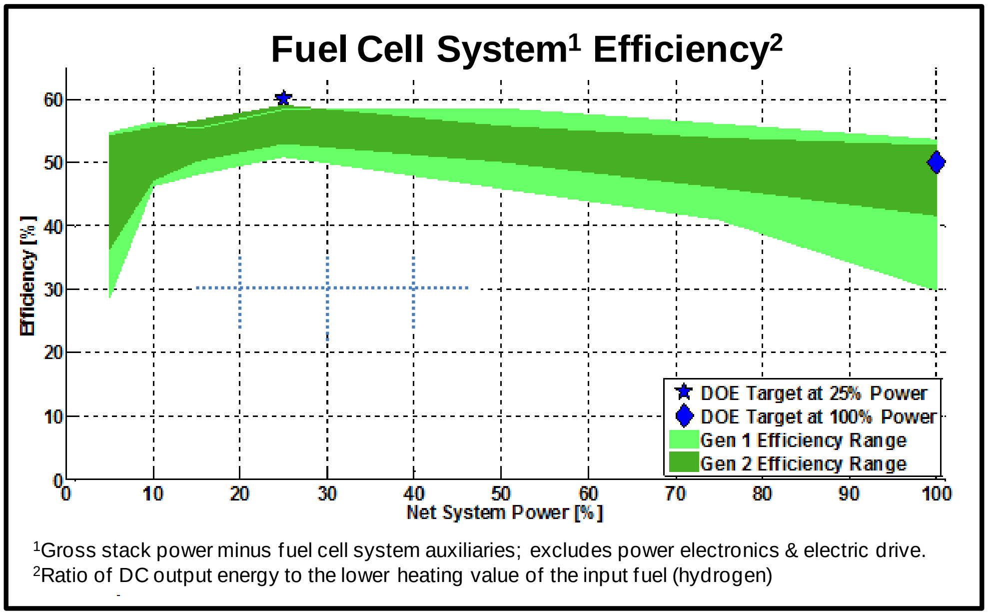

FIGURE F.9 Demonstrated efficiency of vehicle fuel cell systems.
SOURCE: Wipke et al. (2010a,b).

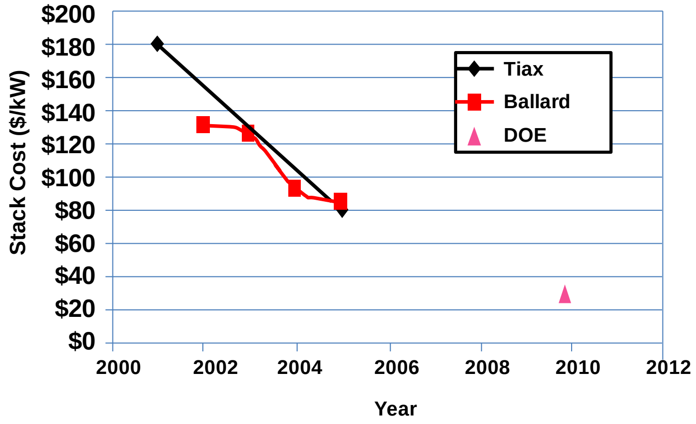

FIGURE F.10 Historical progression of high-volume fuel cell stack cost projections.
SOURCES: Tiax (Carlson et al., 2005; Ballard Power Systems, 2006).

F.4.1.4 Fuel Cell System Cost: 2010

Detailed analyses of fuel cell system designs, material costs, component costs, and manufacturing and assembly costs (Carlson et al., 2005; Kromer and Heywood, 2007) previously estimated 2005 fuel cell costs to be $67/kW. But recent technology developments aimed at cost reduction and improved detailed cost analyses (James et al., 2010; Carlson et al., 2005) have resulted in estimates for high-volume fuel system cost dropping to $51/kW in 2010. The fuel cell stack generally accounts for 50-60 percent of the system cost. Figure F.10 shows how projections of costs for high-volume stack production have declined as the technology has improved. Figure F.11 shows recent estimates of costs for fuel cell stacks and systems as a function of production volume.

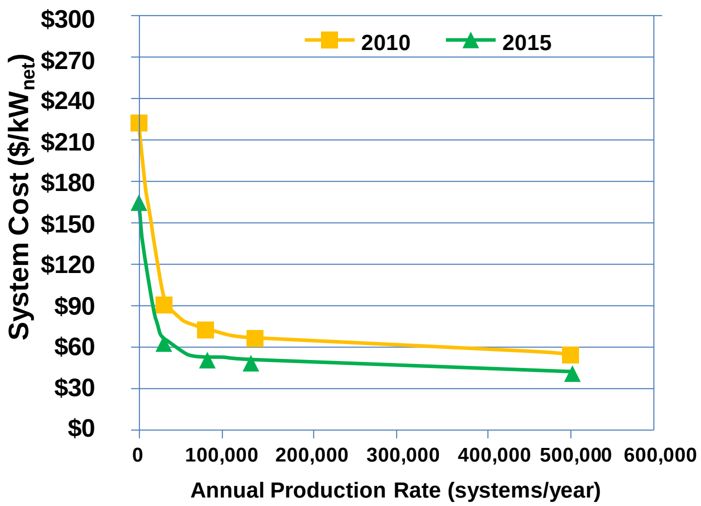

FIGURE F.11 Progression of fuel cell system costs with production volume.
SOURCE: James et al. (2010).

F.4.1.5 Onboard Hydrogen Storage: 2010

For onboard storage of hydrogen fuel, the physical storage of hydrogen as a compressed gas (35 or 70 MPa), has emerged as the technology path for the introduction of FCEVs (Hua et al., 2011; Jorgensen, 2011) because (1) it can release hydrogen at the required maximum rate and adjust to rapid changes in demand; (2) the time required to fill the tank is comparable to the time required to fill gasoline or diesel fueled vehicles; (3) energy losses during fueling, de-fueling, and long-term parking are minimal; and (4) compressed storage has been demonstrated in fleets of FCEVs.

The storage capacity, and hence the vehicle driving range, is limited by the volume and cost of tanks that can be packaged in vehicles. However, driving ranges over 300 miles are expected to be achieved. For example, in 2007 Toyota demonstrated a five-passenger FCEV with 70 MPa storage that traveled 350 miles in on-road conditions. Industry standards for fueling stations have been developed (e.g., SAE J2600 and J2601) and demonstrated at commercial public vehicle fueling stations offering hydrogen and gasoline pumps in the United States (Washington, D.C., California, and Michigan) and Germany (Munich, Frankfurt, and Berlin).

Carbon-fiber reinforced composite tanks have been employed to achieve sufficient strength for 70 MPa containment at manageable weight. Permeation is managed with an interior liner made either from a metal (e.g., aluminum) or a polymer (e.g., high-density polyethylene). Detailed cost analyses (Hua et al., 2011) show total system costs of \$2,900 for representative 35 MPa systems (5.6 kg usable H_2 stored; \$15/kWh, \$518/kg-H_2) and \$3,500 for 70 MPa systems (5.6 kg usable H_2 stored; \$19/kWh, \$625/kg-H_2) as shown in Figure F.12. Carbon fiber, priced at roughly \$30/kg, accounts for most of the cost of the CFRC wrapped layers that provide the structural strength of the storage system. The remaining costs are primarily attributed to flow-regulating hardware.

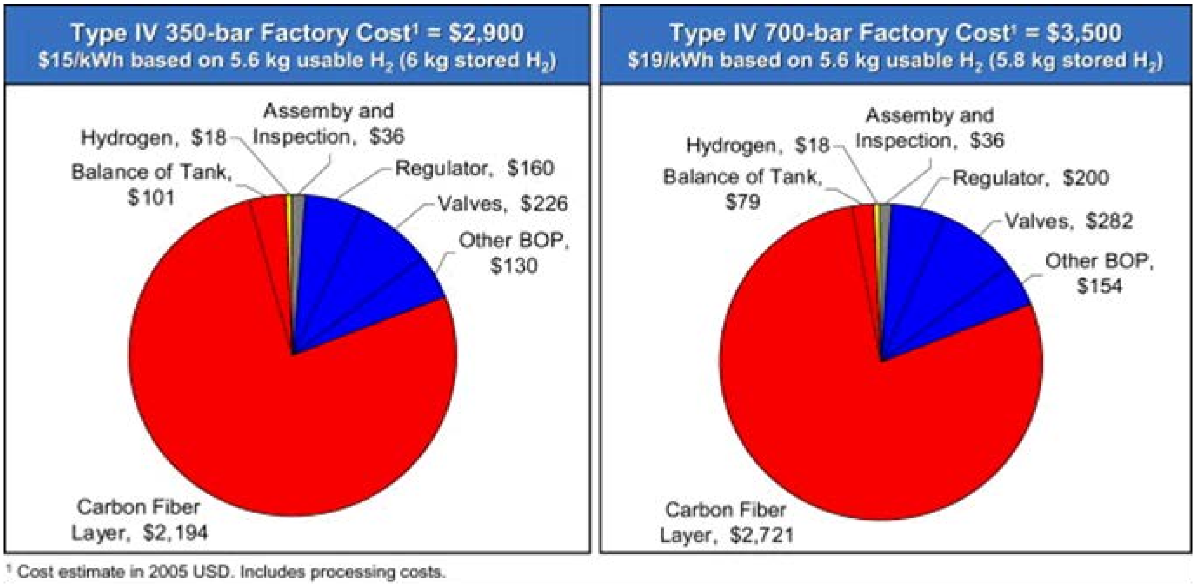

FIGURE F.12 Breakdown of compressed hydrogen storage system costs at high-volume production using 2010 technology.
SOURCE: Hua et al. (2011).

F.4.1.6 Vehicle Safety

The two primary features that distinguish FCEVs from conventional ICE vehicles with respect to safety are high-voltage electric power and hydrogen fuel. Safety of high-voltage electric power is managed on FCEVs similarly to HEVs, where safety requirements have resulted in on-road safety comparable to conventional ICE vehicles. Experience from decades of safe and extensive use of hydrogen in the agriculture and oil refining industries has been applied to vehicle safety and verified in vehicle maintenance and on-road demonstration programs. Fire risk is mitigated by the high dissipation rate of hydrogen, which is greater than gasoline fumes, and regulatory provisions for fuel system monitoring. Safety of high pressure onboard gaseous fuel storage has been demonstrated worldwide in decades of use in natural gas vehicles. Comparable safety criteria and engineering standards, as applied to ICEs, HEVs, and natural gas vehicles, have been applied to FCEVs (for example, Society of Automotive Engineers industry specifications: J1766, J2578, J2579, J2600, J2601, and J2719; and International Organization for Standardization specifications 14687-2, 15869, and 20100). The United Nations has drafted a Global Technical Regulation for hydrogen-fueled vehicles to provide the basis for globally harmonized vehicle safety regulations for adoption by member nations.

F.4.2 FCEV Cost and Efficiency Projections 2020-2050

F.4.2.1 2020-2030 Fuel Cell System Cost

Detailed analyses of current costs and expected technology advances that are already under demonstration have resulted in a fuel cell system cost estimate of $39/kW for a high-volume FCEV commercial introduction in 2015 (James et al., 2010). This estimate reflects recent advances in technology and material costs; for example, in both the cost and loading of precious metal in fuel cell

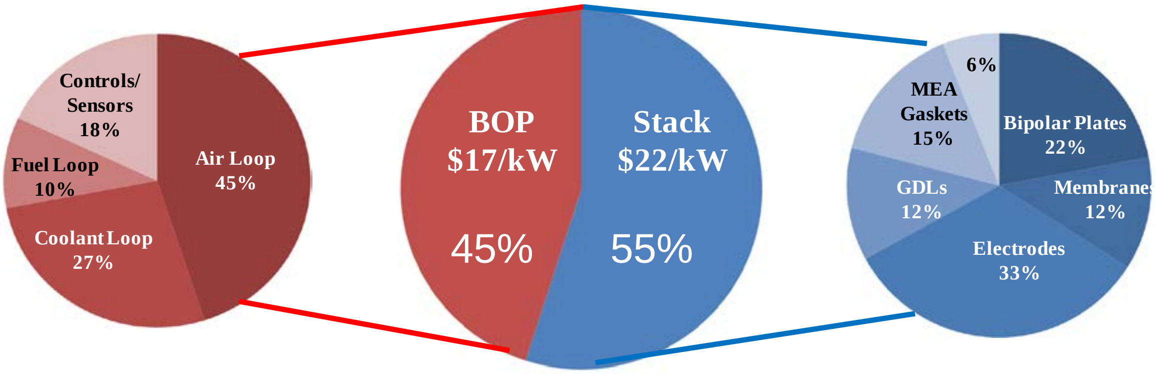

FIGURE F.13 Breakdown of fuel cell system costs at high-volume production using 2015 technology (stack power density 1000 mW/cm^2 with 0.15 mg/cm^2 Pt loading).
SOURCE: James et al. (2010).

electrodes. The platinum (Pt) loading in an earlier-generation stack with ~80 g Pt at $32/g (2005 Pt price) would cost ~$2,500. If only 10 g Pt were required in a higher-technology alloyed-Pt stack, the cost would be only ~$600, even at the higher 2011 Pt price of $58/g.

Figure F.13 shows the main sources of costs expected in 2015 for high-volume production. The total cost then is projected to be $39/kW. This report assumes $40/kW for the midrange in 2020. The optimistic case for 2020 is $36/kW, anticipating additional cost benefit from potential near-term technology developments, which are shown in Table F.29. All costing assumes commercial introduction of FCEVs at annual production volumes over 200,000 units, with the primary economy of scale occurring at 50,000 units (James et al., 2010).

Estimates for 2030 costs of fuel cell systems vary with optimism for the timing of technology advances currently under development. Projections of fuel cell system cost up to 2030 are linked to the achievement of technology advances already under development (see Table F.29, “Near-Term” and “Mid-Term”). An important and unique attribute of the automotive fuel cell system is the early stage in its development and application for on-road vehicles. Historically, gains in weight, volume, efficiency, and cost between successive early generations of a new technology are much more substantial than between more mature generations as early designs and materials are rapidly simplified, transformed and refined. Estimates of 2-3 percent per year reductions in high volume cost in early generations of a technology and 1 percent per year in later generations have commonly been observed (EPA, DOT, CARB, 2010). Therefore, for purposes of this report, technology-driven cost reduction from 2020 to 2030 of 2 percent per year is midrange, and 3 percent per year is optimistic. These advances are considerably less than the recent rate of fuel cell cost reduction (Figure F.10), because observed documented trends in technology cost apply to technologies that are market ready, not to technologies in a pre-commercial prototype stage of development. The technology-driven cost projections for fuel cell systems are summarized in Table F.30.

The fuel cell system costs are traditionally expressed as $/kW, because the change in cost of a system has generally been proportional to changes in vehicle power over the limited ranges of power currently used in FCEVs (James et al., 2010). However, significant deviation from a linear dependence of cost on net system power over a large range of vehicle power is expected for significant variations in vehicle power. This nonlinearity is difficult to project and is not included in cost estimation for this report. Nonlinearities are currently thought to be of secondary significance,[52] but there is little experience or analysis to substantiate that assumption.

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[52] The committee received confidential input from vehicle manufacturers and suppliers.

TABLE F.29 Currently Recognized Opportunities for Technology Development for Improved Energy Efficiency and Cost

Near Term (2020)

1. Storage—reduced carbon fiber usage in storage systems—improved winding patterns
2. Storage—improved methods for tank production
3. Storage and fuel cell system—simplified design (fewer and cheaper components)
4. Storage and fuel cell system—improved manufacturing processes
5. Fuel cell system—reduced use of platinum (platinum alloys; new catalyst structures)
6. Fuel cell system—reduced transport losses by refined management of reactant flows and hydration and improved electrode structure
7. Fuel cell system—optimized stack and balance of plant (BOP) with optimized battery supplement for transient power
8. Fuel cell system—reduced BOP size and complexity from optimized reactant flow fields (for decreased stoichiometry and resultant lower mass flow rates)
9. Fuel cell system—reduced BOP size and complexity from membranes tolerant of lower humidity and/or higher temperature operation (simplified water management, lower pressure, and smaller radiator)
10. Fuel cell system—catalyst structures that increase and maintain the effective surface area of chemically active materials
11. Fuel cell system—higher temperature membranes for increased activity with less catalyst

Mid-Term (2030)

1. Storage—reduced cost of carbon fiber—new production and processing methods
2. Storage—reduced carbon fiber usage in storage systems—smaller or lower-pressure vessels (associated with increased fuel cell system efficiency)
3. Storage—efficient low pressure cryo-storage
4. Fuel cell system—new durable membrane materials for low cost volume manufacture, thin design and low resistance
5. Fuel cell system—rapid manufacturing techniques for layered materials and for integration of layered materials into unit pieces for quick assembly
6. Fuel cell system—low cost, conductive, chemically stable plate materials
7. Storage and fuel cell system—capacity downsizing related to reduction in vehicle weight and increased efficiency of fuel cell system
8. Further progress in near-term opportunities

Long Term (2050)

1. Fuel cell system—catalysts that do not use precious metals
2. Fuel cell system—capability for efficient operation at less than 1.2 stoichiometry
3. Fuel cell system—novel, low cost thermal management
5. Fuel cell system—refined designs for fluid flow in fuel cell stacks
6. Fuel cell system—new membrane materials and processing methods
7. Fuel cell system—novel processing techniques for catalyst substrates, impregnation and integration With layered materials
8. Storage—new low cost, high strength composite materials
9. Further progress in near-term and mid-term opportunities

F.4.2.2 2050 Fuel Cell System Cost

Projections for 2050 shown in Table F.30 are based on technology achievements and refinements outlined in Table F.29 and on historical trends for cost improvement with advancing generations of mature technologies and manufacturing refinements (EPA, DOT, CARB, 2010). Historical trends include continuing technology advancement with further research and advances in new materials, analysis, simulation, and testing tools. Because of the expected major focus of fuel cell R&D on cost reduction prior to 2030, it is expected that subsequent cost reduction rates will not exceed norms for more mature generations of technologies (EPA, DOT, CARB, 2010). Therefore both midrange and optimistic cost estimates for 2050 include the 1 percent per year cost reduction rate associated with maturing technologies after 2030.

Evaluation of potential world Pt supply to support FCEVs as 50 percent of the on-road LDV sales by 2050 was conducted by TIAX (Carlson et al., 2003), assuming the conservative achievement of 15 g Pt per FCEV by 2050. Key documented findings are the following: (1) there are sufficient Pt resources in the ground to meet long-term projected Pt demand; (2) the Pt industry has the potential for expansion to meet demand for 50 percent market penetration of FCEVs (15 g Pt/vehicle) by 2050; and (3) the price of Pt may experience a short-term rise in response to increasing FCEV penetration, but is expected to return to its long-term mean once supply adjusts to demand. Scaled to 10 g Pt per FCEV (already achieved by 2010), the same conclusions apply to 80 percent penetration of the LDV sales by 2050.

F.4.2.3 2020-2050 Fuel Cell System Efficiency

Near-term technology developments for fuel cell systems are expected to be focused on reduction in fuel cell system cost without significant gain in fuel cell efficiency. Therefore, the midrange 2020 fuel cell system efficiency is taken to be 53 percent, which is equivalent to the 2010 estimated on-road fuel cell system efficiency. The optimistic 2020 fuel cell system efficiency is taken to be 55 percent, reflecting minimal expectation for efficiency gains while resources are focused on cost reduction. 55 percent is consistent with a minimal 0.5 percent per year improvement in the loss fraction over the nominal 2010 efficiency in the DOE demonstration fleet. Due to the primary focus on cost reduction, projections for both 2030 and 2050 midrange and optimistic efficiencies are expected to reflect only minimal 0.5 percent per year reduction in the loss fraction from the respective 2020 values. Fuel cell system efficiency projections are summarized in Table F.31.

TABLE F.30 Summary Fuel Cell System Cost Projections ($/kW)

	2010	2020	2030	2050
Midrange	51	40	33	27
Optimistic	51	36	27	22

TABLE F.31 Summary of Fuel Cell Efficiency Projections

	2010	2020	2030	2050
Midrange	53%	53%	55%	60%
Optimistic	53%	55%	57%	62%

F.4.2.4 2020-2030 Hydrogen Storage Cost

The cost of a CFRC hydrogen storage tank varies with the pressure and volume capacity. At present, nominal storage of 5.6 kg of 70 MPa hydrogen costs ~$3,500 (Hua et al., 2011). Reduction in the cost of tanks can be expected from new manufacturing/design techniques and smaller hydrogen storage systems. Storage systems get smaller as vehicle demand for fuel is reduced with improved vehicle efficiency (vehicle weight, aerodynamics, rolling resistance and powertrain efficiency).

Significant cost reduction from technology advancement within the 2010-2020 period is not expected due to current plans and capabilities of manufacturers for onboard storage.[53] The midrange hydrogen storage cost for 2020 is derived from the 2010 estimated cost by scaling the system to contain the volume of hydrogen needed to maintain vehicle driving range with the vehicle efficiency projected for 2020. The scaling is accomplished by recognizing that roughly 75 percent of storage cost is proportional to the volume of stored hydrogen (variable cost); the remaining 25 percent of cost (boss and valve hardware) is not changed by the quantity of stored hydrogen (fixed cost is not sensitive to vehicle efficiency) (Hua et al., 2011). This assumes that a reduction in volume of stored hydrogen is accomplished by reducing tank size rather than eliminating a tank. This is consistent with consideration of packaging constraints for moderate reductions in vehicle demand. Dividing the cost into fixed and variable fractions is a means of approximating nonlinearities in the dependence of the storage system cost on its volumetric capacity when variations in that capacity are not small.

Estimates for midrange and optimistic 2030 technology-driven costs of hydrogen storage differ because of different estimates of the timing of technology advances currently under development (Warren, 2009) (Table F.29, “Near-Term” and “Mid-Term”). Several improvements in processing techniques have been identified (Warren, 2009) that are expected to reduce the cost of carbon fiber used in CFRC by 25 percent. That reduction is applied as a 1 percent per year midrange cost improvement from 2020 until 2040 to accommodate the technology development and its phased-in implementation into high-volume production. The 2030 optimistic cost projection assumes 2 percent per year technology-driven cost reduction from 2020 to 2030 in the variable cost fraction to accommodate full deployment of these new techniques for manufacture of carbon fiber by 2030.

However, less expensive manufacturing techniques are needed for producing carbon fiber from polyacrylonitrile or other precursor materials and for manufacturing storage tanks from the carbon fibers. Project success and commercialization of redesigned storage systems by 2030 are not certain but eventually could reduce storage costs significantly.

The fixed cost fraction, which is associated with flow-control equipment, is expected to have modest potential for cost reduction, because the technologies are mature. Therefore, a 1 percent per year cost reduction is applied to be consistent with historical improvements (EPA, DOT, CARB, 2010) in the design and materials used in mature technologies as they are applied in new areas, such as the 70 MPa compressed hydrogen application. The result is a projected 10 percent cost reduction in the fixed cost fraction over the 2020-2030 period.

In addition to these technology-related cost projections, additional reductions can be expected when the storage system is downsized—when the volume of hydrogen that needs to be stored for full vehicle range is reduced in response to increased vehicle efficiency. This reduction in the variable fraction of the storage cost is directly proportional to the reduced vehicle load. The difference between cost projections with and without downsizing of the storage system is illustrated by the difference between Tables F.32 and F.33.

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[53] The committee received confidential input from vehicle manufacturers and suppliers.

TABLE F.32 Technology-Driven Storage Cost Projections (constant 5.6 kg hydrogen capacity)

	2010	2020	2030	2050
Midrange	5.6	5.6	5.6	5.6
Cost $	3,500	3,500	3,165	2,589
$/kg-$H_2$	625	625	565	462
$/kWh	19	19	17	14
Optimistic				
Cost $	3,500	3,500	2,936	2,232
$/kg-$H_2$	625	625	524	399
$/kWh	19	19	16	12

TABLE F.33 Illustrative Hydrogen Storage System Cost Projections[a] from Technology Advances (Design, Material, and Manufacturing) and Reduced Size (Hydrogen Capacity)

	2010	2020	2030	2050
Midrange				
Capacity (kg)	5.5	4.6	3.8	2.8
Cost ($)	3,453	3,031	2,402	1,618
$/kg-$H_2$	628	659	632	578
$/kWh	19	20	19	17
Optimistic				
Capacity (kg)	5.5	4.4	3.3	2.4
Cost ($)	3,453	2,938	2,055	1,326
$/kg-$H_2$	628	668	623	553
$/kWh	19	20	19	16

[a] Costs based on illustrative hydrogen storage capacity requirements.

F.4.2.5 2050 Hydrogen Storage System Cost

The midrange estimate for 2050 hydrogen storage cost results from continuation of the technology-driven 1 percent per year cost improvement over the 2030-2050 period in recognition of research into improvements in CRFC winding patterns[54] and expectation of further improvements in manufacturing costs from added experience with high-volume production using new techniques (Warren, 2009). The result is an accumulated technology-driven cost reduction from 2020 to 2050 of 26 percent. As before, additional cost reductions result when the variable fraction of the storage system cost is scaled to accommodate the downsizing of storage associated with continually improving vehicle efficiency.

The optimistic estimate for 2050 hydrogen storage cost assumes a more aggressive technology-driven 2 percent per year cost improvement applied to the variable cost fraction for an additional 10-year

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[54] The committee received confidential input from vehicle manufacturers and suppliers.

period prior to 2050 in anticipation of aggressive research to reduce the cost of structural carbon or to find replacement materials or alternatives to compressed gaseous storage. Research on cost reduction of structural CFRC is expected to accelerate with the new market driver of its broadened application to airplane fuselages. And low pressure cryo-storage could become commercially viable.

Greater cost reductions are possible with manufacturing breakthroughs for carbon fiber, but that is not assumed here. However, it is noted that a reduction in storage cost associated with achievement of a targeted <$10/kg carbon fiber and pressure shift to 50 MPa would be consistent with a cost reduction of 35-40 percent, the optimistic technology-driven projection in Table F.32.

F.4.2.6 Trade-Offs with BEVs

FCEVs, like BEVs, are electric vehicles having no GHG emissions. Both are "fueled" by an energy carrier (electricity or hydrogen) that can be produced from a myriad of traditional and renewable energy sources (biofuels, natural gas, coal, and solar-, hydro-, and nuclear power). Three primary considerations differentiate their prospects for introduction and acceptance as LDVs: vehicle attributes, infrastructure, and rate of technology development.

- *Vehicle attributes*. FCEVs provide the full utility of current on-road vehicles. BEVs, however, require time consuming "refueling" (recharging) and only offer limited driving range between "refuelings." In addition, FCEVs can be used to power a residence or business (or hydrogen fueling station) during electrical outages and, thereby, provide a form of back-up for the electrical grid, rather than the adding load for BEV recharging. Indeed, during an electrical outage caused by a winter storm, for example, a BEV could not be recharged to drive to a region with power and warm shelter.
- *Infrastructure*. FCEV commercialization will require the installation of hydrogen fueling pumps (with supporting onsite fuel storage and fueling equipment) at conventional fueling stations. In addition, a significant installation of regional facilities for production of hydrogen will be required. BEV commercialization requires installation of charging stations in homes or secure and accessible locations, upgrade of neighborhood transformers, and increase in electrical generating capacity for vehicle charging outside today's off-peak hours. Infrastructure considerations are discussed further in Chapter 3 of this report. Long-term customer acceptance of in-home, near-home, and workplace/shopping charging installations remains to be established. Home chargers can be provided with individual vehicle sales, allowing vehicle manufacturers to somewhat decouple BEV sales from reliance on an independent deployment of infrastructure. However, FCEV sales will depend on the availability of hydrogen fueling stations and, hence, will require large-scale coordination of infrastructure and vehicle producers.
- *Rate of technology development*. A key requirement for realization of projected technology advances for battery and fuel cell systems is the continued dedication of R&D resources. Because demand for improved battery technologies is driven by their established application in portable communication/computer devices, prospects for short-term return on R&D investments are substantial.

In contrast, commercial application of fuel cell systems in vehicles is not seen as an outgrowth of communication/computer technologies. Instead, it depends on the likelihood of a substantial transition of the transportation sector to hydrogen fueled vehicles. The assessment of the prospects for such a transition likely depends on whether government energy policy signals a commitment to support deployment of hydrogen infrastructure and vehicles. Otherwise, the continued dedication of substantial private R&D resources to fuel cell vehicle technologies may not continue to support the current rate of progress in fuel cell technologies.

Projections of the timing and magnitude of improvements in efficiency and cost of fuel cell systems and the cost of hydrogen storage systems, as discussed in this chapter, are based on the fundamental assumption that resources—private and government—dedicated to R&D in support of fuel cell vehicles and hydrogen infrastructure are maintained at current levels or greater.

F.4.3 Cost and Performance Evolution of a Fuel Cell Electric Vehicle

As with BEVs, fuel cell vehicles currently are considerably more expensive than conventional ICEVs but have the potential to drop substantially in cost. The key factors in this expected cost reduction (aside from vehicle load reductions, which affect all vehicle regardless of drivetrain type) are expected improvements in efficiency and cost reductions in general electric drivetrain components (e.g., batteries and motors), expected strong increases in fuel cell efficiency, and strong expected cost reductions in fuel cell stacks and onboard storage costs. As shown in Table F.34, the overall effect of these factors will be to reduce vehicle costs by about $5,300-$6,600 by 2050, allowing fuel cell vehicles to have lower costs than their conventional ICE drivetrain competitors in 2050 (and possibly as early as 2030). Gasoline-equivalent fuel economy can range upwards of 170 mpg by 2050 and exceed 200 mpg in the optimistic case.

TABLE F.34 Details of the Potential Evolution of a Midsize Fuel Cell Vehicle, 2010-2050

	2010	2030 mid	2030 opt	2050 mid	2050 opt
Fuel cell efficiency	53	55.3	57.5	59.6	61.6
Fuel economy, test mpg_e	94.1	125.8	149.5	170.4	211.3
Fuel cell power required, kW	110.8	91.6	85.6	81	71.2
Hydrogen required for 390 mile (test) range, kg	4.3	3.1	2.6	2.3	1.9
Fuel cell cost, $/kW	50	33	27	27	22
Variable hydrogen tank cost, $/kg	469	424	383	347	283
Incremental cost versus baseline, $	8,554	3,747	2,133	3,281	1,961
Incremental cost versus conventional, $	8,554	1,314	−62	−378	−1,442

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G

Fuels

G.1 RENEWABLE FUEL STANDARD

The federal Renewable Fuel Standard (RFS) was created under the Energy Policy Act of 2005 because Congress recognized "the need for a diversified portfolio of substantially increased quantities of … transportation fuels" to enhance energy independence (P.L. 109-58). RFS required an increase use of renewable fuels from 4.0 billion gallons per year in 2006 to 7.5 billion gallons in 2012 (Figure G.1). Because what constitutes "renewable" is determined by a set of legal definitions, the RFS was designed to encourage the consumption of a specific type of non-petroleum based alternative fuel (that is, biofuels). The U.S. biofuel consumption from 2006 to 2008 exceeded the RFS consumption mandates.

The Energy Independence and Security Act of 2007 (EISA 2007) was enacted "to move the United States toward greater energy independence and security" and to "increase the production of clean renewable fuels." EISA 2007 amended the RFS, creating what is referred to as RFS2 by modifying the program in several key ways:

- It expanded the RFS program to include diesel, in addition to gasoline, produced in or imported into the United States;
- The amendment extended the time horizon to 2022.
- The incremental volumes of renewable fuel required to be consumed have increased to 10.6 billion gallons of ethanol equivalent fuels plus 0.5 billion gallons of biomass-based diesel in 2008 and 35 billion gallons of ethanol equivalent plus 1 billion gallon of biomass-based diesel in 2022;
- It established four categories of renewable fuel based on the feedstock source and on life-cycle GHG emission thresholds. There are separate volume requirements for each one (Figure G.1).

The four renewable fuel categories are nested within the mandate and are differentiated by the reduction in life-cycle greenhouse gas (GHG) emissions using the methodology developed by U.S. Environmental Protection Agency (EPA; Federal Register 40 CFR part 80, p. 14669) and include indirect land-use changes distributed over the expected 30 year life of the biofuel refineries. The four categories are (Figure G.1) as follows:

- *Conventional biofuels*, usually ethanol derived from starch of corn grain (corn-grain ethanol). Conventional biofuel produced from facilities that commenced construction after December 19, 2007, would have to achieve at least a 20 percent reduction in life-cycle GHG emissions compared to petroleum-based gasoline and diesel to qualify as a renewable fuel under RFS2. The quantities are measured in terms of ethanol equivalent gallons.
- *Advanced biofuels*, which are renewable fuels other than corn-grain ethanol, achieve at least a 50 percent reduction in life-cycle GHG emissions. Advanced biofuels can include ethanol and other types of biofuels derived from such renewable biomass as cellulose, hemicellulose, lignin, sugar, or any other

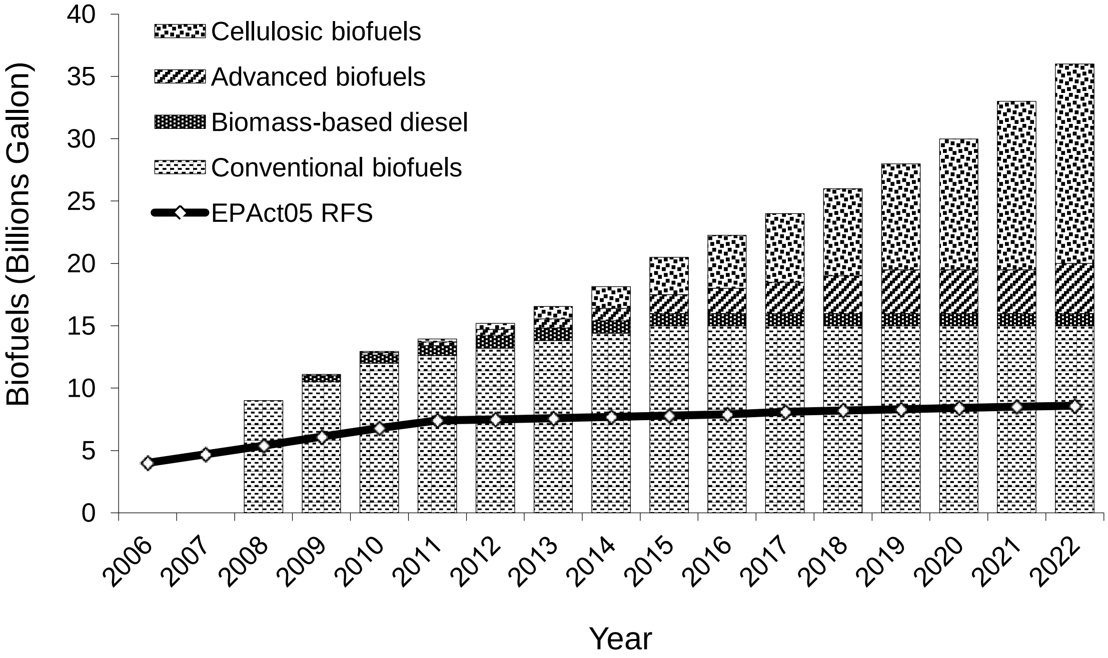

FIGURE G.1 Mandated consumption target for different categories of biofuels under the Energy Independence and Security Act of 2007.
NOTE: The line shows the consumption target under the Energy Policy Act of 2005 (EPAct05 RFS).
SOURCE: NRC (2011).

starch that is not from corn, biomass-based diesel, and coprocessed renewable diesel.[1] The mandate requires 4 billion gallons per year of advanced biofuels measured in terms of ethanol equivalent gallons in 2022.

- *Cellulosic biofuels* are renewable fuels derived from any cellulose, hemicellulose, or lignin from renewable biomass that achieve at least a 60 percent reduction in life-cycle GHG emissions. In general, cellulosic biofuels also qualify as renewable fuels and advanced biofuels. The mandate requires 16 billion gallons per year of cellulosic biofuels measured in terms of ethanol equivalent gallons in 2022.
- *Biomass-based diesel,* including biodiesel[2] made from vegetable oils or animal fats and cellulosic diesel, achieves at least a 50 percent reduction in life-cycle GHG emissions—for example, soybean biodiesel and algal biodiesel. Co-processed renewable diesel is excluded from this category. The mandate currently requires 1 billion gallons per year of biodiesel expressed as gallons of methyl ester-based biodiesel energy equivalents.

While corn-grain ethanol is only allowed to fulfill the conventional biofuels volume, biofuels from other categories could also fill the conventional biofuels volume if cellulosic biofuels become less expensive than corn-grain ethanol. There is not a specific mandate for corn-grain ethanol.

RFS2 also defines the energy equivalence of various biofuels relative to ethanol. One gallon of biodiesel is worth 1.5 gallons of ethanol. One gallon of renewable diesel[3] is worth 1.7 gallons of ethanol. One gallon of biobutanol is worth 1.3 gallons of ethanol. Other fuels are rated by petition to EPA based

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[1] Co-processed renewable diesel refers to diesel made from renewable material mixed with petroleum during the hydrotreating process.

[2] Biodiesel is a diesel fuel consisting of long-chain alkyl esters derived from biological materials such as vegetable oils, animal fats, and algal oils.

[3] Renewable diesel is they hydrogenation product of triglcerides derived from biological materials.

on their energy content relative to ethanol. Therefore, the mandate can be met with lower volumes of fuels with higher energy contents.

RFS2 requires that all renewable fuels be made from feedstocks that meet a new definition of renewable biomass. In EISA 2007, the definition of renewable biomass incorporates land restrictions for planted crops, crop residue, planted trees and tree residue, slash and precommercial thinnings, and biomass from wildfire areas. Detailed definitions and EPA's interpretations of the terms are found in *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule* (EPA, 2010a: pp. 14691-14697). A brief version of EISA's renewable biomass definition and land restrictions is includes the following:

- Planted crops or crop residues that were cultivated at any time prior to December 19, 2007, on land that is either actively managed or fallow and nonforested.
- Planted trees and tree residue from actively managed tree plantations on non-federal land cleared at any time prior to December 19, 2007, including land belonging to an Indian tribe or an Indian individual, which is held in trust by the United States or subject to a restriction against alienation imposed by the United States.
- Slash and precommercial thinnings from non-federal forestlands, including forestlands belonging to an Indian tribe or an Indian individual, that are held in trust by the United States or subject to a restriction against alienation imposed by the United States.
- Biomass obtained from the immediate vicinity of buildings and other areas regularly occupied by people, or of public infrastructure, at risk from wildfire.
- Algae.

G.2 INFRASTRUCTURE INITIAL INVESTMENT COST

As shown in Chapter 3, the investment cost per gallon of gasoline equivalent (gge) per day to build the fuel infrastructure is sizable for all of the alternate fuel and vehicle pathways. Table G.1 shows this cost in 2030 for each fuel expressed in the cost per gge/day, or in the case of electricity cost per kilowatt-hour per day. The costs shown in Table G.1 reflect only the investment costs that involve building a new form of infrastructure needed to use the fuel as a transportation fuel, not those for expanding an already large and functioning infrastructure associated with its more traditional use.

- *Electricity*. Home charger and public charger costs are included. Expansions of producing, transmitting, and distributing electricity and expansions to produce more of the base fuel are not (natural gas, coal, wind, and solar) are not included. A cost for a parking space for access to charging also is not included.
- *Hydrogen.* Costs to convert the base fuel (natural gas, coal, biomass or electricity) to hydrogen are included, carbon capture and storage (CCS) is included when used, and costs to distribute and to deliver hydrogen to the vehicle are included. Expansions to produce more of the base fuel are not included.
- *Natural gas.* Costs for new natural gas stations to deliver this fuel to a vehicle are included. Expansions of the natural gas producing and transmission system are not included.
- *GTL.* Costs to convert natural gas to gasoline are included. Expansions of the natural gas producing and transmission system and the gasoline station costs are not included.
- *CTL.* Costs to convert coal to gasoline are included. CCS is included. Expansions of the coal producing and delivery system and the gasoline station costs are not included.
- *Biofuels.* Costs to convert biomass to liquid fuels are included. Expansions of the biomass growing, collecting and delivery systems and the gasoline station costs are not.

- *Gasoline (new plant).* New refinery cost to convert crude oil to gasoline are included for comparison. Costs of producing crude oil and gasoline station costs are not.

The overall infrastructure investment needs for a vehicle using any of the fuels in Table G.1 is found by multiplying this investment cost by the fuel (gge) consumed per day. Using 13,000 miles per year for all vehicles, 4.0 miles per kilowatt-hour (kWh) for electric vehicles (EVs), 80 miles/gge for HFCVs, and 40 miles/gge for liquid fuel vehicles to reflect approximate 2030 mileage rates shown in the Chapter 5 Reference Case, the investment costs per vehicle are shown in Tables G.2 and G.3.

G.3 POLICY AREAS TO BE ADDRESSED TO INCREASE THE SHARE OF ALTERNATIVE FUELS USED IN LIGHT-DUTY VEHICLES

From the fuels perspective, policy areas where actions are required to progress along the path of research and development, demonstration, deployment, and rapid growth for each of the alternate fuels. Policy actions need to address, in an effective manner, each of the areas marked with an X or the fuel pathway is unlikely to grow to maturity with production in low-GHG methods (Table G.4).

G.4 POTENTIAL AVAILABILITY OF BIOMASS FOR FUELS

Several potential sources of non-food biomass can be used to produce biofuels. They include crop residues such as corn stover and wheat straw, fast-growing perennial grasses such as switchgrass and *Miscanthus*, whole trees and wood waste, municipal solid waste, and algae. Each potential source has a production limit.

Several studies have been published on the estimated the amount of biomass that can be sustainably produced in the United States. All of the studies focused on meeting particular production goals, and none of them project biomass availability beyond 2030. For example, the objective of the report *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (commonly referred to as the “billion-ton study”) was to determine the feasibility of producing sufficient biomass to reduce petroleum consumption by 30 percent (Perlack et al., 2005). That study estimated that 1 billion tons of biomass would be needed to displace 30 percent of the U.S. petroleum consumption in 2005. The four studies that were analyzed in the report *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy* (NRC, 2011) focused on the feasibility of producing sufficient biomass to meet the RFS2 mandates in 2022. All those studies concluded that sufficient RFS-compliant biomass would be available to produce biofuels for meeting the consumption mandate. None of these studies attempted to estimate the maximum production rates that could be attained if the RFS2 biomass restrictions were eliminated or if different economic assumptions, such as a carbon tax, were made.

The 2009 report *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (NAS-NAE-NRC, 2009) evaluated the role of biofuels in America’s energy future. The panel assessed the potential availability of biomass feedstock that would not incur competition for land with crops or pasture and for which the environmental impact of biomass production for biofuels was no worse than the original land use. They concluded that 550 million dry tons of cellulosic feedstock could be sustainably produced for biofuels in 2020. The billion-ton study (Perlack et al., 2005) was recently updated and the *U.S. Billion Ton Update* was released in 2011 (DOE, 2011). As in the first study, its objective was to estimate if 1 billion tons of biomass could be sustainably and economically produced in the lower 48 states by the year 2030. Projections beyond 2030 were not made, and the study did not attempt to estimate maximum biomass that could be harvested. The updated study defined “economic production” as all material that could be produced at or below a farm-gate price of $60/dry ton. This is not an *average* biorefinery feedstock price, but is a maximum price at the farm or

TABLE G.1 2030 Fuel Infrastructure Investment Costs, $/gge per day

Alternate Fuel	2030 Investment Cost, $/kWh per day or $/gge per day
Electricity (PHEV-10)	370 $/kWh per day
Electricity (PHEV-40)	530 $/kWh per day
Electricity BEV	330 $/kWh per day
Hydrogen (with CCS)	3,890 $/gge per day
Natural gas (CNG)	910 $/gge per day
GTL	1,900 $/gge per day
CTL/CCS	2,500 $/gge per day
Biofuel (thermochemical)	3,100 $/gge per day
Gasoline (new plant—if needed)	595 $/gge per day

TABLE G.2 2030 Fuel Infrastructure Investment Costs per Vehicle

Alternate Fuel	Fuel Use/Day, kWh/day or gge/day	Infrastructure Investment Cost per Vehicle, $
Electricity (PHEV-10)	1.75 kWh/day	$650
Electricity (PHEV-40)	5.4 kWh/day	$2,880
Electricity BEV	8.92 kWh/day	$2,930
Hydrogen (with CCS)	0.45 gge/day	$1,370
Natural gas (CNG)	0.89 gge/day	$810
GTL	0.89 gge/day	$1,690
CTL	0.89 gge/day	$2,220
Biofuel (thermochemical)	0.89 gge/day	$2,760
Gasoline (new plant—if needed)	0.89 gge/day	$530

TABLE G.3 2030 Fuel Infrastructure Investment Costs per Vehicle—Highest to Lowest

Alternate Fuel	2030 Investment Cost, $/gge per day or $/kWh per day	Car Fuel Use/Day, gge/day or kWh/day	Infrastructure Investment Cost, $/Vehicle
Electricity BEV	330 $/kWh per day	8.92 kWh/day	$2,930
Electricity (PHEV-40)	530 $/kWh per day	5.45 kWh/day	$2,880
Biofuel (thermochemical)	3,100 $/gge per day	0.89 gge/day	$2,760
CTL	2,500 $/gge per day	0.89 gge/day	$2,220
Hydrogen (with CCS)	3,890 $/gge per day	0.45 gge/day	$1,750
GTL	1,900 $/gge per day	0.89 gge/day	$1,690
Natural gas (CNG)	910 $/gge per day	0.89 gge/day	$810
Electricity (PHEV-10)	370 $/kWh per day	1.75 kWh/day	$650
Gasoline (new plant—if needed)	595 $/gge per day	0.89 gge/day	$530

TABLE G.4 Policies Areas to be Addressed to Increase the Share of Alternative Fuels Used in Light-Duty Vehicles

	Biofuels	Electricity for PHEVs	Hydrogen	CNG	GTL	CTL/CCS
Consistent RD&D support to advance technology development and lower costs.	X		X[a]	X[b]	X	X
Actions to facilitate demonstration of new fuels technology at small commercial scale.	X		X[c]			
Actions to ensure continued research, development, demonstration and deployment of CCS.[d]		X	X			X
Actions to encourage the initial deployment of the fuel infrastructure to coincide with vehicle introductions and early growth.	X[e]	X[f]	X[g]	X		
Actions to reduce the consumer price of alternate fuels at the beginning of a transition to encourage the use in existing vehicles or new vehicle types.	X[h]		X		X	X
Following successful fuel/vehicle introductions, when large quantities of fuel are needed, actions that limit GHGs associated with producing the fuel.	X[i]	X	X			

NOTE: Yellow, policy is in place; green, policy is partly in place or could be improved; and blue, policy is needed

[a] DOE funding has not been consistent.

[b] DOE funding has not been consistent, but the new Advanced Research Projects Agency-Energy program is beginning.

[c] Small demonstrations have been made but not at nearly commercial scale.

[d] Research and development is being done but commercial viability is not yet demonstrated.

[e] RFS2 addresses this issue.

[f] Programs to install public chargers in some locations. May need to be expanded.

[g] California is addressing this through mandated station construction.

[h] RFS2 addresses this issue.

[i] RFS2 addresses this issue.

forest gate. At least a portion of the biomass production would be available at a lower cost. The cost to produce biofuels based on a feedstock price of $75 to $133 per dry ton at the refinery gate is discussed later in this appendix. Two scenarios were evaluated at the price ceiling of $60 in the *U.S. Billion-Ton Update*: a baseline case that assumed an annual crop yield growth of 1 percent and a high crop yield case that assumed a 2 to 4 percent annual yield improvement in commodity crops and energy crops. The study also accounted for biomass that was currently being used to produce energy. The projected availabilities of biomass for fuels from the two studies are summarized in Figure G.2.

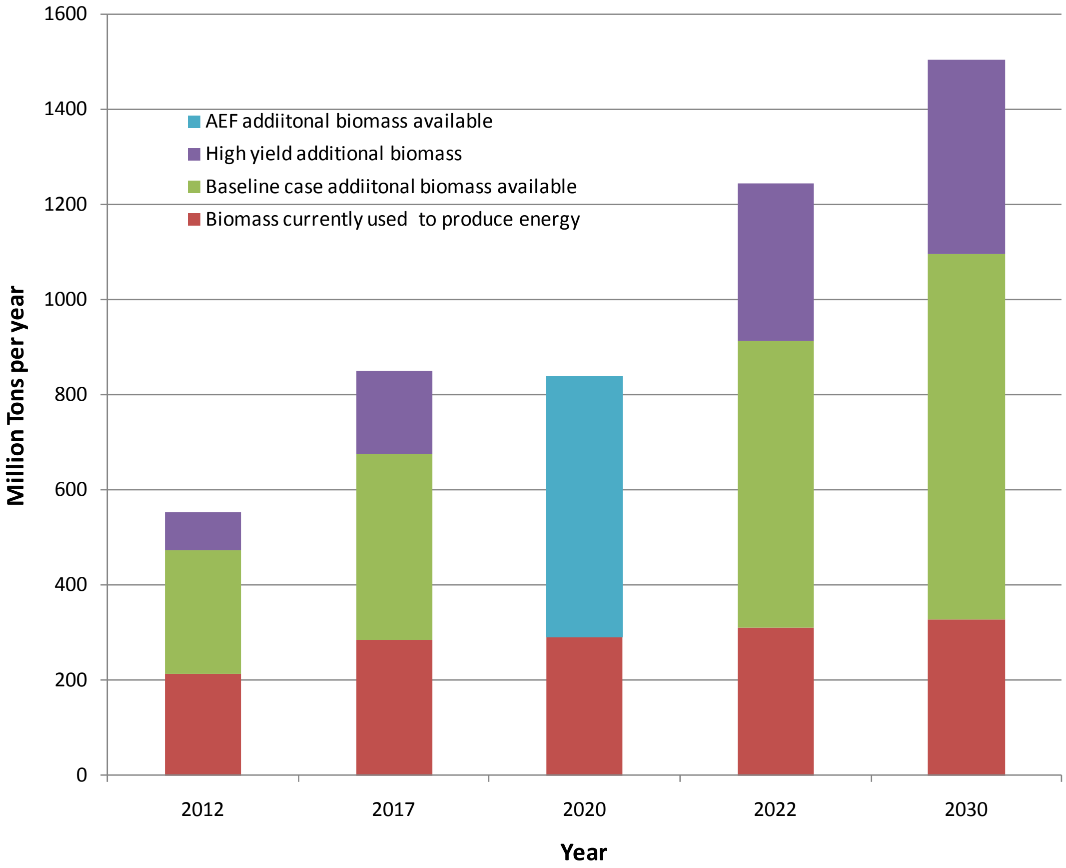

FIGURE G.2 Biomass availability estimates from the *U.S. Billion-Ton Update* (DOE, 2011) from the report *Liquid Fuels for Transportation from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (NAS-NAE-NRC, 2009). NOTE: Data for years 2012, 2017, 2022, and 2030 are from DOE (2011) and the estimated biomass availability for biofuel production from NAS-NAE-NRC (2009) for the year 2022 is added on top of the biomass projected to be used for electricity generation.

The estimate in the NAS-NAE-NRC report (2009) is consistent with the billion-ton study baseline case when interpolated to the same year. If the billion-ton study *baseline case* (which includes a 1 percent annual increase in biomass productivity) is linearly extrapolated to 2050, then 1350 million tons of additional biomass (above that currently used for energy production) are projected to be available to produce biofuels in 2050.

U.S. Billion-Ton Update (DOE, 2011) primarily analyzed biomass production from energy crops and forest and agricultural residue recovery. Its estimate of biomass availability for cellulosic biofuels in 2022 is comparable to the 550 million dry tons that the NAS-NAE-NRC (2009) report estimated for 2020. By 2030, the baseline case of the study (which includes a 1 percent annual yield growth) concluded that an additional 767 million dry tons of biomass would be available at prices of less than $60 per ton. The production of additional biomass would require a shift of 22 million acres of cropland and 41 million acres of pasture land into energy crop production by 2030. That report concluded that at $60 per ton, none of the existing wood products would be diverted to fuel production. At higher prices, however, some pulpwood and lumber would begin to be diverted to fuel use.

There is other evidence, however, that a substantial amount of forest biomass could be utilized for biofuels production. With the economic downturn, a decrease of almost a 100 million dry ton per year in U.S. wood production (harvest) was observed between 2008 and 2010 (Figure G.3). This additional forest biomass was not included in the billion-ton study projections.

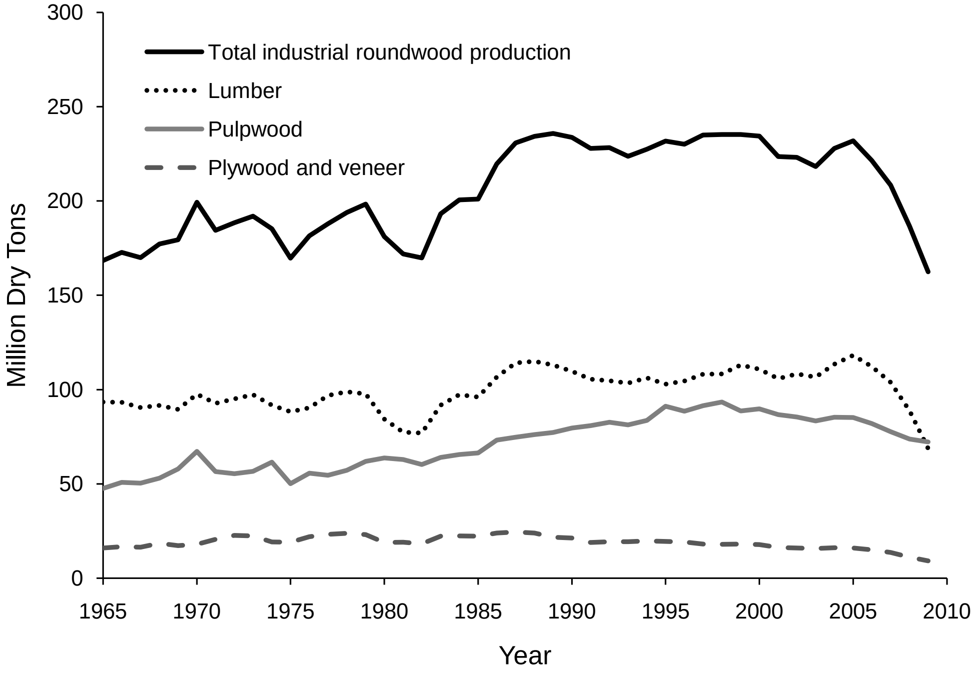

FIGURE G.3 U.S. industrial wood production.
DATA SOURCE: Howard (2007); updated data to 2009 as result of personal communication.
FIGURE SOURCE: NRC (2011).

Annual removals from U.S. forestlands, including roundwood products, logging residues, and other removals from growing stock and other sources, were estimated to be about 21.2 billion cubic feet annually, which is about 320 million dry tons of biomass. This level of harvest is well below net annual forest growth and only a small fraction of the total timberland inventory (Figure G.4). In 2006, the ratio of forest-growing stock growth (wood volume increases) to growing stock removals (for example, harvest and land clearing) in the United States was 1.71, which indicates that net forest growth exceeded removals by 71 percent (Smith et al., 2009). The 320 million dry ton removal does not match the wood production, because part of the total wood removal is residue that is being used to produce energy. Because about 320 million dry tons per year are being produced each year and forest mass is increasing at a ratio of 1.71, based on 2007 harvest rates, an additional 225 million tons per year could be removed. If harvest rates in 2012 were at least 75 million tons lower than that in 2007, a total of over 300 million tons of forest biomass would be available sustainably with no land-use change.

Many estimates of potential biomass availability have been made, but to accurately predict how much biomass will actually be supplied for biofuel production at any future date is extremely difficult. There appears to be consensus among studies that sufficient biomass could be produced to meet the 2022 RFS2 consumption mandate). Meeting the RFS2 mandate will require an additional 200-300 million dry tons per year of biomass.

Another source of biomass for fuel is microalgae and cyanobacteria (DOE, 2010b; Singh and Gu, 2010). Microalgae are produced commercially as nutritional supplements and for cosmetics (Spolaore et al., 2006; Earthrise, 2009). Many companies are pursuing the commercial production of algal biofuels (USDA-RD, 2009; DOE, 2010a,b). At present, algal biofuels are further from commercial deployment than cellulosic biofuels, and their costs have been estimated to be $10-$20 per gallon of diesel (Davis et al., 2011). Therefore, algal biofuels are not considered in this detail in this report.

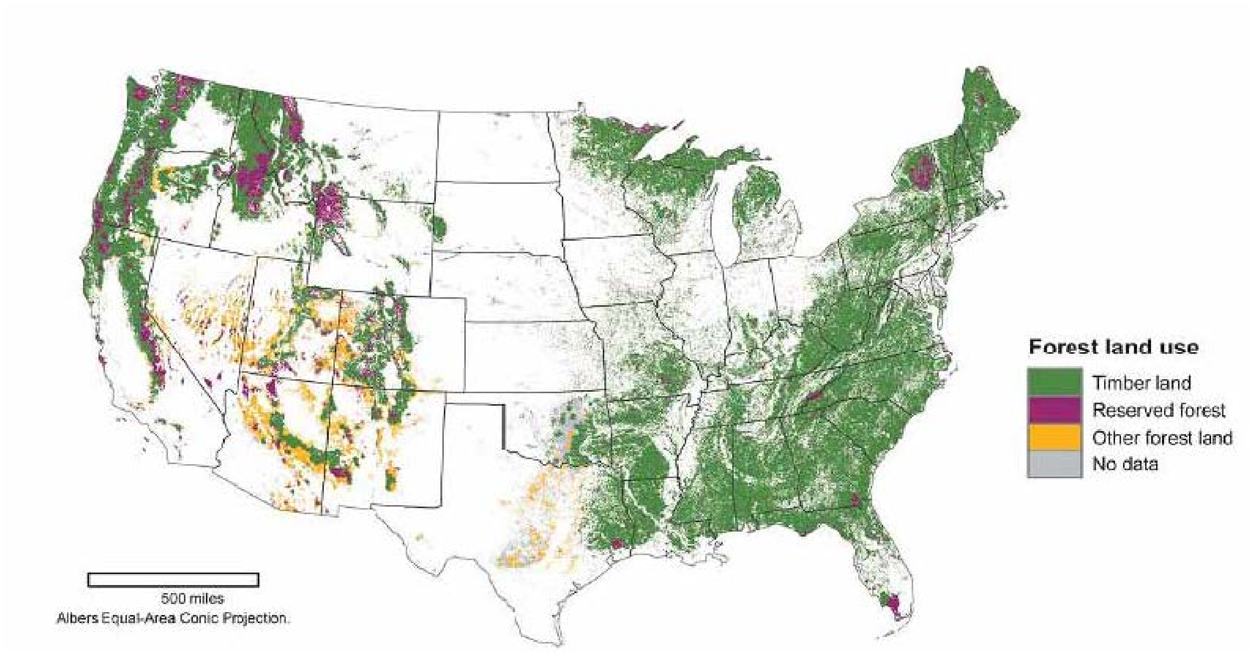

FIGURE G.4 Forest resources of the United States. In the United States, there are about 750 million acres of forestland, with slightly more than two-thirds classified as timberland or land capable of producing 20 cubic feet per acre annually of industrial wood products in natural stands (Smith et al., 2009). Another 22% of this forestland is classified as “other” and is generally not productive enough for commercial timber operations owing to poor soils, lack of moisture, high elevation, or rockiness. The remaining 10% of forestland is withdrawn from timber utilization by statute or administrative regulations and is dedicated to a variety of non-timber uses, such as parks and wilderness. The timberland fraction of U.S. forestlands totals approximately 514 million acres. As noted by Smith et al. (2009), the map above shows forested pixels from the USDA Forest Service map of Forest Type Groups (Ruefenacht et al., 2008). Timberland is derived and summarized from RPA plot data using a hexagon sampling array developed by EPA. Reserved land is derived from the Conservation Biology Institute, Protected Areas Database. Other forestland is non-timberland forests.
SOURCE: DOE (2011 p. 18).

G.5 ESTIMATING GREENHOUSE-GAS EMISSION IMPACTS OF BIOFUELS

Ascertaining the net GHG emission impact of biofuels is challenging because of the complexities in fully characterizing the GHG effects associated with the supply chain and management practices and the interactions with real-world markets for commodities and land. Attributional life-cycle assessment (LCA) calculations based on direct emissions generally find that, if efficiently produced, biofuels have a lower GHG emission impact than the fossil fuels they replace. However, the adequacy of an attributional LCA for reliably assessing the GHG impacts of fuels is being called into question, with GHG emission effects from land-use changes being a major area of uncertainty. Complex LCA calculations, including estimated changes in land use induced by increasing use of biomass as an energy source, have shown variable results because of different assumptions on the magnitude of the changes, the amount of GHG emitted, and the time frame considered. (See for example, the Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis; EPA, 2010b).

Direct land-use changes can be estimated based on land area that would have to be converted from some other use to grow a given amount of biomass. For this analysis, three types of cellulosic biomass are assumed to be harvested or grown in the United States for biofuel production: crop residue (mostly corn stover), woody biomass, and switchgrass (to represent high-yield perennial grasses). The production of crop residue and woody biomass is assumed to be scaled up with little if any net GHG

BOX G.1 Examples of Indirect Land-Use Changes from Increasing Biofuel Production

Domestic

Increased corn production in the Midwest to supply ethanol production could induce the withdrawal of land from the Conservation Reserve Program to grow wheat that has been displaced by the expansion of corn production for feedstocks (Marshall et al., 2011).

Domestic and International

Biofuel-induced land-use changes can occur indirectly if land use for production of biofuel feedstocks causes new land-use changes elsewhere through market-mediated effects. The production of biofuel feedstocks can constrain the supply of commodity crops and raise prices, thus triggering other agricultural growers to respond to market signals (higher commodity prices) and to expand production of the displaced commodity crop. This process might ultimately lead to conversion of nonagricultural land (such as forests or grassland) to cropland. Because agricultural markets are intertwined globally, production of bioenergy feedstock in the United States could result in land-use and land-cover changes elsewhere in the world. If those changes reduce the carbon stock in vegetation, carbon would be released in the atmosphere when land-use change occurs (NRC, 2011).

emissions directly attributable to land-use change within the United States. Corn stover is a coproduct of corn production and up to certain proportions[4] can be diverted for feedstock production while requiring no additional land. Woody biomass harvests are assumed to be restricted to levels that can be obtained from existing tree plantations, thinnings, and other forest waste without displacing other uses. Switchgrass cultivation can be planted on currently unmanaged pasture land or abandoned cropland with little impact on cropland. However, simulations of crop yields suggest that the highest productivities of switchgrass would be achieved in the highest-producing agricultural lands in the country (Thomson et al., 2009; Jager et al., 2010). There is no guarantee that switchgrass would not displace food crops. Growing dedicated bioenergy crops could be a better management for some unmanaged pasture or abandoned cropland than their current use, because dedicated bioenergy crops can have deep root systems and sequester carbon in soil.

The GHG emissions of most concern and uncertainty are the secondary emissions that result from displacement of food crops by bioenergy feedstock (for example, corn, soybean, and switchgrass) or from biofuel-induced market mediated effects, commonly referred to as indirect land-use change (ILUC). (See Box G.1 for examples.) The United States is a major exporter of food grain and feedstuff. Any reduction in commodity-crop production in the United States by the diversion of land from food and feedstuff production to biofuel production could force an increase in food production in other parts of the world. Of the 767 million incremental tons of biomass estimated to be available in the *U.S. Billion-Ton Update,* 367 tons (48 percent) were from forest and crop residue with no direct or indirect land-use change.

Global economic models have been used to predict the biofuel-induced market-mediated land use changes in the United States and other countries that can be attributed to increased biofuels production in the United States (EPA, 2010b; Hertel et al., 2010; Marshall et al., 2011). These models generally predict a cascading effect whereby pasture land in other countries, such as Brazil, are converted to crop land and tropical forests are cleared of old growth to replace the pasture land. The net effect is a loss of existing carbon stocks associated with tropical forests, grasslands, or wetlands. These emissions are associated with increases in biofuel supply and peak shortly after the market-mediated land-use changes occur, although carbon releases from soil and forgone sequestration can continue for many years. The emissions associated with feedstock production and processing, biofuel refining, transport and distribution, and tailpipe emissions are ongoing.

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[4] The proportion of corn stover that can be harvested without compromising soil quality depends on the soil type, slope and other factors.

TABLE G.5 GHG Emission from Indirect Land-Use Changes

	GHG Emission Caused by Indirect Land-Use Change (kg CO_2 eq Per Million Btu Biofuel Distributed Over 30 Years)		
Biomass Crop	Minimum	Maximum	Mean
Corn grain	21	46	32
Sugar cane	-5	12	4
Switchgrass	9	23	16
Soy oil	15	76	43

SOURCE: EPA (2010b).

The magnitude and timing of these ILUC conversions is difficult to predict. Thus, they are typically represented as ranges under varying assumptions. These ranges, as estimated by the EPA for the RFS2 final rule (EPA, 2010b), are shown in Table G.5. Crop residues such as corn stover, wheat straw, and forest residue are assumed to be harvested at levels that do not negatively affect soil quality and do not incur GHG emissions from land-use change.

Because ILUC emissions are related to biofuel expansion, they raise one of the contentious issues in the debate over LCA for GHG emissions of biofuels—that is, the proper accounting of the GHG emissions over the life of a biofuel production system. The estimates in Table G.5, as in the case of many published studies on GHG emissions as a result of ILUC (Searchinger et al., 2008; EPA, 2010b; Hertel et al., 2010), are based on an analysis of emission effects over an assumed future time period. The amortization period was typically chosen to represent the life of a biofuel production system. EPA and the California Air Resource Board used a 30-year period and the European Union’s analyses use a 20-year period (EPA, 2010b). Combining such amortized values with annual emission rates to provide estimates of GHG emission in a given year would not reflect the actual emission in that given year.

Because the scenarios developed in this report use a model that computes annual emissions for different vehicle-fuel systems, if the analysis is to reflect GHG emissions from ILUC, it needs to estimate the annual emissions impacts as biofuel capacity expansion occurs. When land is converted as a secondary effect of biofuel expansion (that is, ILUC), a large initial CO_2 release occurs in the year the land is cleared, followed by smaller releases and foregone sequestration over a number of subsequent years. The resulting cumulative release is often referred to as the “carbon debt” associated with the expansion of a bioenergy system. If the direct process emissions associated with the biofuel production system are lower than those of the displaced fossil fuel, then the carbon debt gets “repaid” over time.

This situation is illustrated by EPA in its regulatory impact assessment of RFS2 (EPA, 2010b; Figure 3-15). Figure G.5 shows a life-cycle GHG accounting method for corn-grain ethanol. The large first-year GHG emissions takes 14 years to be repaid by the GHG benefits of corn-grain ethanol instead of petroleum-based fuels.

For the purpose of approximating annual emissions impacts for biofuel scenarios, an assumption is made here that the ILUC emissions associated with an expansion of biofuel capacity all occur in the first year. Specifically, the mean 30-year average values contained in the RFS2 final rule are multiplied by 30 and released in the first year of biorefinery operation. This is also not a true representation of what would most likely happen, but rather an extreme case. In reality, the land conversion would not be immediate at biorefinery start-up, but would occur gradually as a result of economic drivers over several years. The values of GHG emissions from ILUC used in this report also assume that the majority of the land is cleared for an alternate use by “slash and burn” techniques. That is, all the existing biomass is cut down and burned in place. If the land is being converted because of economic drivers, it is probably better to assume that at least some of the standing timber would be harvested rather than burned in place. This would reduce the first year ILUC impact.

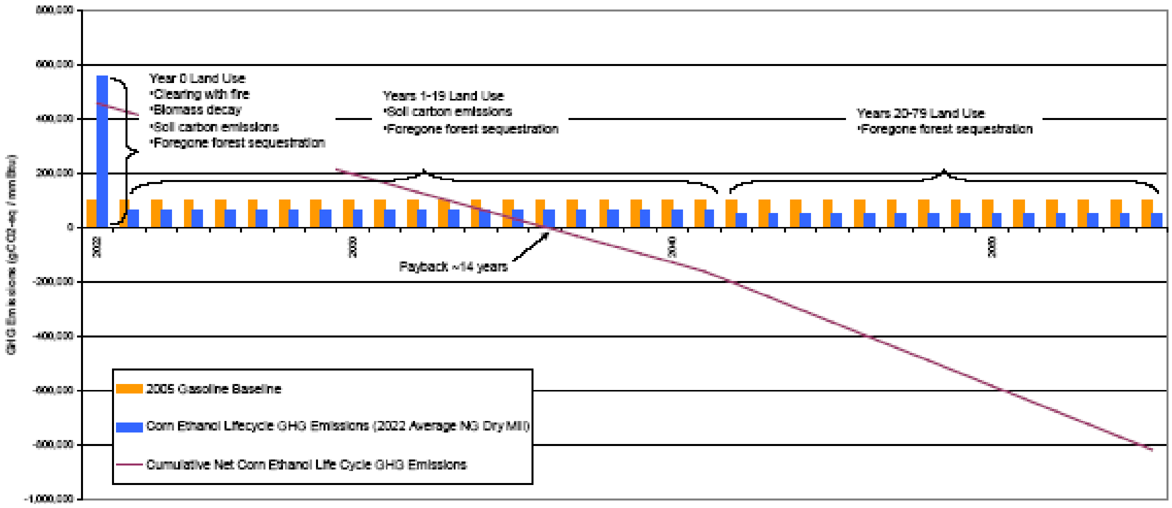

FIGURE G.5 Corn ethanol payback period.
SOURCE: Figure 2.6-14 from EPA (2010b).

Over long time periods, the different methods of accounting for ILUC-related GHG emission converge. ILUC emissions only occur as a result of increases in production capacity. At the end of the 30th year after the last increase in biofuel-production capacity, the accounting method that assumes a carbon debt in the first year that ILUC was incurred actually estimates larger GHG emission reductions from biofuels than the method that amortize the carbon debt over 30 years used by EPA and others. The 30-year amortization method implies that the initial ILUC-related GHG emissions are spread over the 30-year life of the biorefinery and continue to occur at 1/30 of the initial ILUC if the biorefinery continues to operate beyond 30 years. However, the 30-year amortization method underestimates cumulative GHG emissions over any time period when the biofuel expansion is ongoing. Therefore, the simplified first-year front-loading of ILUC-related GHG emissions is more in line with the importance of avoiding emissions sooner rather than later to minimize climatic risk (which is a scientific rationale for rapid GHG emissions reduction proposals analogous to those of this committee's task statement).

Two different biofuel expansion cases are investigated in the modeling of this study. In the first case, biofuel-production capacity only expands to meet the RFS2 consumption mandates. This expansion is assumed to begin in 2011 and be complete for corn ethanol by 2013. Cellulosic-biofuel production to meet RFS2 is assumed to begin in 2015 and expand at an annual investment rate of about $10 billion per year (about 0.8 billion gallons per year of "drop-in" biofuels to meet the advanced and cellulosic biofuel requirements of 12.9 billion gge/year (20 billion gallons of ethanol equivalent per year by 2030) in RFS2.

In the second case, all future biofuels beyond the 15 billion gallons of corn-based ethanol are assumed to be produced from cellulosic biomass. Construction again begins in 2015, but investment is at the higher rate of about $10 billion per year. This investment rate would produce about 45 billion gge/year of drop-in biofuels by 2050, in addition to the 15 billion gallons per year of corn-grain ethanol that will be produced. That volume of cellulosic biofuels is required to meet the study objective of 80 percent reduction in use of petroleum-based fuels. The 45 billion gge/year of "drop-in" fuels will require 703 million dry tons of biomass per year.

The annual GHG emission profiles of these two expansion scenarios are given in Table G.6, which includes annual values for the calculated WTW GHG emissions relative to petroleum-based gasoline on a gallon of gasoline equivalent basis. WTW GHG emissions for petroleum-based gasoline are 98 kg CO_2e/MMBtu or 11.38 kg CO_2e/gge.

Although not analyzed here, another point to keep in mind is that all indirect land-use change attributable to biofuel system expansion is actually direct land-use change attributable to other uses in the location where it occurs. Land-use changes are driven in part by economic reasons; thus, it is reasonable

TABLE G.6 GHG Emissions for Biofuels Relative to Petroleum-Based Fuels

	Only Meeting RFS2					
	Corn-Grain Ethanol		"Drop-In" Cellulosic Biofuels		Maximum Biofuels	
Year	Billion Gallons Per Year	Percent GHG Reduction Compared to Petroleum-Based Fuels	Billion gge/year	Percent GHG Reduction Compared to Petroleum-Based Fuels	Billion gge/year	GHG Reduction Compared to Petroleum-Based Fuels
2010	13	48.0				
2011	14	118				
2012	15	113				
2013	15	48.0				
2014	15	48.0				
2015	15	48.0	0.8	507	1.9	507
2016	15	48.0	1.6	260	3.8	560
2017	15	48.0	2.3	177	5.8	177
2018	15	48.0	3.1	136	7.7	136
2019	15	48.0	3.9	111	9.6	111
2020	15	48.0	4.7	95.8	11.5	94.8
2021	15	48.0	5.5	83.1	13.4	83.1
2022	15	48.0	6.3	74.2	15.4	74.2
2023	15	48.0	7.0	67.4	17.3	67.4
2024	15	48.0	7.8	61.9	19.2	61.9
2025	15	48.0	8.6	57.4	21.1	57.4
2026	15	48.0	9.1	53.6	23.0	53.6
2027	15	48.0	10.2	50.4	25.0	50.4
2028	15	48.0	10.9	47.7	26.9	47.7
2029	15	48.0	11.7	45.4	28.8	45.4
2030	15	48.0	12.5	43.3	30.7	43.3
2031	15	48.0	12.5	12.4	32.6	41.5
2032	15	48.0	12.5	12.4	34.6	39.9
2033	15	48.0	12.5	12.4	36.5	38.4
2034	15	48.0	12.5	12.4	38.4	37.1
2035	15	48.0	12.5	12.4	40.3	35.9
2036	15	48.0	12.5	12.4	42.2	34.9
2037	15	48.0	12.5	12.4	44.2	33.9
2038	15	48.0	12.5	12.4	46.1	33.0
2039	15	48.0	12.5	12.4	48.0	32.2
2040	15	48.0	12.5	12.4	49.9	31.4
2041	15	48.0	12.5	12.4	51.8	30.7
2042	15	48.0	12.5	12.4	53.8	30.0
2043	15	48.0	12.5	12.4	55.7	29.4
2044	15	48.0	12.5	12.4	57.6	28.9
2045	15	48.0	12.5	12.4	59.5	28.3
2046	15	48.0	12.5	12.4	61.4	27.8
2047	15	48.0	12.5	12.4	63.4	27.4
2048	15	48.0	12.5	12.4	65.3	26.9
2049	15	48.0	12.5	12.4	67.2	26.5
2050	15	48.0	12.5	12.4	69.1	26.1

to expect that some of the wood in cleared forests might be harvested and used for other purposes rather than being immediately burned, as assumed in the ILUC calculations. This consideration would both reduce the first year GHG emissions and spread out the remaining emissions over a longer period of time.

This study also assumes that the ILUC attributable to cellulosic biofuels is that of switchgrass production. According to the *U.S. Billion Ton Update*, almost half of the biomass will be sourced from crop and forest residue (DOE, 2011). These biomass sources and some amount of farmed trees have little if any ILUC associated with their use, so the ILUC emissions estimated in this study could be high by a factor of two.

During the biomass conversion process, about 50 to 75 percent of the energy content of the biomass is burned during the production of the biofuel. Applying CCS technology to the biofuel production facilities would further reduce the GHG emissions attributable to biofuels. In addition, the LCA GHG emission calculations assume the current emissions profile from electricity generation and that all transportation fuels used to grow, harvest, and transport the biomass are produced from petroleum. As the electricity grid is decarbonized and the biofuel industry expands, the emissions from these sources will decrease as would the overall GHG emissions from biofuels.

G.6 INVESTMENT COSTS OF ELECTRICITY AS FUEL FOR ELECTRIC VEHICLES

There are four potential sources of investment costs for electricity as fuel to EVs:

- The charging stations to transfer energy from the electric power system to the vehicle.
- Additions or changes to the transmission and distribution system uniquely attributable to charging EVs.
- Additional generation capacity to charge EVs.
- Conversion of the existing power generation sources to a low GHG emitting set.

G.6.1 Charging Station Costs

The cost of installing a charging station consists of two parts: purchase of the physical charging station itself and installation of the charging station. The cost of the charging station is straightforward, but the cost of installation is highly variable. For the purpose of this study, an average of currently available charging station costs and the midrange estimate of expected installation costs was used. Cost of the equipment will drop in the future, but installation will not necessarily fall very much. We decreased the cost of the equipment by 67 percent in 2050, along a linear trend between 2010 and 2050 (Table G.7).

DC fast charging stations currently cost upwards of $20,000 for the equipment and are expensive to install because they have to connect to a higher voltage line than other charging equipment, and more site modification is expected. The DC charger price is expected to drop as additional large companies enter the market. Since the business case for electricity as fuel is not yet clear, the committee did not try to account for the commercial charging station investment, which is analogous to gasoline filling station costs. Furthermore, large numbers of public fast charging stations may not be required, since they primarily provide reassurance against range anxiety and are likely to primarily be used to connect cities along main travel lines and will not necessarily be widely available within cities. A study released by TEPCO (Botsford and Sczczepanek, 2009) showed that the addition of a second quick DC charger for their fleet in the Tokyo area increased the monthly mileage driven by a factor of 7. However, the number of vehicle charging events did not substantially increase, and the second charger did not receive significant use. Users drove the vehicles to lower battery levels knowing that there was a safety net. Based on these results, as well as user experiences in the United States (Turrentine et al., 2011) and Germany (Blanco, 2010), the committee considered that there will be fewer public chargers needed per vehicles after initial introduction. The committee's specific assumptions are addressed below.

TABLE G.7 Charging Station Costs in 2011

Charging Station	Equipment Range of Costs	Equipment Cost	Installation Range of Costs	Installation Cost	Total Cost Charging Station
Level I—residential	$450-$995	$479	$0-$500	$200	$679
Level II—residential	$490-$1,200	$892	$300-$2,000	$1,300	$2,192
Level II—commercial	$1,875-$4,500	$2,477	$1,000-$10,000	$2,500	$4,977
DC fast charge	$17,000-$44,000	$34,200	$7,000-$50,000	$20,000	$54,200

To convert the charger costs to investment costs, the committee considered six different EVs: plug-in hybrid electric vehicle (PHEV)-10, PHEV-15, PHEV-20, PHEV-30, PHEV-40, and an all-electric BEV. (PHEV-XX is the designation of a PHEV with battery sized for XX miles of electric-only driving.) The committee also considered the two grid cases form the *Annual Energy Outlook* (AEO) 2011 report (EIA, 2011): the conventional grid and the low-GHG grid. Each vehicle is assumed to travel 13,000 miles per year with the fraction of electric miles taken from the NRC study *Transitions to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles* (NRC, 2010): 20 percent electric miles for PHEV-10, 60 percent for PHEV-40, and 100 percent for the all EVs. For each vehicle, the committee assumed mix of charging stations typical for that class of PHEV. For a PHEV-10, one level 1 home charger and 0.25 of a level 1 charger at work was assumed for each vehicle (equaling $849 per vehicle in 2011). For a PHEV-40, one level 2 home charger and 0.4 of a commercial-grade level 2 charger was assumed for each vehicle (equaling $4,183 in 2011). For a battery electric vehicle (BEV), one level 2 home charger, 0.4 of a commercial charger, and 0.001 of a DC fast charger was assumed for each vehicle (equaling $4,725 in 2011). For PHEV-30, PHEV-40, and BEVs, the percentage of a public level II charging station decreases to 0.3 in 2020, 0.2 in 2030, and 0.1 in 2040.

For each vehicle, the committee amortized the cost of this mix of chargers over 15 years to get an annual cost and converted it to a cost per kilowatt-hour (based on the annual energy use of each vehicle. The total cost of electricity into the vehicle is the sum of the charger cost per kilowatt-hour added to the cost of the electricity drawn from the grid, using residential rates in the appropriate year, and tabulated separately for both the reference and low GHG grid. Investment costs are also calculated in units of $/kWh/day and $/gge/day for comparison to other fuel systems. The results are shown in Tables G.8 and G.9 for the reference grid and the low-GHG grid, respectively.

G.6.2 Investment Costs for Transmission and Distribution System Changes Uniquely Required to Accommodate EV Charging

The primary impact will be on the local distribution system; changes to the high voltage transmission system will be included in the cost of new power generation systems and are discussed later in this appendix. As discussed briefly in chapter 3, studies by EPRI (EPRI, 2004, 2005), discussions by the committee with PG&E (Takemasa, 2011), and previous discussions with SCE earlier (Cromie and Graham, 2009) indicate these costs are manageable and within the normal costs of doing business. The continuing replacement, upgrade, and expansion costs are reflected in the cost of electricity provided to customers.

TABLE G.8 Reference Grid

	2010	2020	2035	2050
PHEV-10				
AEO base elec cost, $/kWh	0.096	0.088	0.092	0.094
Charger cost, $/car	849	748	598	448
Charger cost, $/kWh	0.066	0.058	0.047	0.035
Into LDV elec cost, $/kWh	0.162	0.146	0.139	0.129
AEO GHG, $MMTCO_2$	2499	2418	2753	3042
WTT GHG $kgCO_2$/kWh	0.631	0.582	0.594	0.592
WTT GHG, kg CO_2/gge	21.06	19.42	19.85	19.78
Investment, $/kWh/day	362	319	255	191
Investment, $/gge/day	12317	10862	8679	6495
PHEV-15				
AEO base elec cost, $/kWh	0.096	0.088	0.092	0.094
Charger cost, $/car	849	748	598	448
Charger cost, $/kWh	0.048	0.042	0.034	0.025
Into LDV elec cost, $/kWh	0.144	0.130	0.126	0.119
AEO GHG, $MMTCO_2$	2499	2418	2753	3042
WTT GHG $kgCO_2$/kWh	0.631	0.582	0.594	0.592
WTT GHG, kg CO_2/gge	21.06	19.42	19.85	19.78
Investment, $/kWh/day	260	230	183	137
Investment, $/gge/day	8853	7807	6238	4669
PHEV-20				
AEO base elec cost, $/kWh	0.096	0.088	0.092	0.094
Charger cost, $/car	849	748	598	448
Charger cost, $/kWh	0.038	0.034	0.027	0.020
Into LDV elec cost, $/kWh	0.134	0.122	0.119	0.114
AEO GHG, $MMTCO_2$	2499	2418	2753	3042
WTT GHG $kgCO_2$/kWh	0.631	0.582	0.594	0.592
WTT GHG, kg CO_2/gge	21.06	19.42	19.85	19.78
Investment, $/kWh/day	208	184	147	110
Investment, $/gge/day	7082	6246	4990	3735
PHEV-30				
AEO base elec cost, $/kWh	0.096	0.088	0.092	0.094
Charger cost, $/car	4183	3411	2606	1926
Charger cost, $/kWh	0.139	0.113	0.087	0.064
Into LDV elec cost, $/kWh	0.235	0.201	0.179	0.158
AEO GHG, $MMTCO_2$	2499	2418	2753	3042
WTT GHG $kgCO_2$/kWh	0.631	0.582	0.594	0.592
WTT GHG, kg CO_2/gge	21.06	19.42	19.85	19.78
Investment, $/kWh/day	760	620	474	350
Investment, $/gge/day	25854	21085	16111	11906
PHEV-40				
AEO base elec cost, $/kWh	0.096	0.088	0.092	0.094
Charger cost, $/car	4183	3411	2606	1926
Charger cost, $/kWh	0.123	0.100	0.077	0.057
Into the LDV elec cost, $/kWh	0.219	0.188	0.169	0.151
AEO GHG, $MMTCO_2$	2499	2418	2753	3042
WTT GHG kg CO_2/kWh	0.631	0.582	0.594	0.592
WTT GHG, kg CO_2/gge	21.06	19.42	19.85	19.78
Investment, $/kWh/day	673	549	419	310
Investment, $/gge/day	22888	18666	14262	10539
Battery Electric				
AEO base elec cost, $/kWh	0.096	0.088	0.092	0.094
Charger cost, $/car	4237	3460	2646	1957
Charger cost, $/kWh	0.076	0.062	0.047	0.035
Into the LDV elec cost, $/kWh	0.172	0.150	0.139	0.129
AEO GHG, $MMTCO_2$	2499	2418	2753	3042
WTT GHG kg CO_2/kWh	0.631	0.582	0.594	0.592
WTT GHG, kg CO_2/gge	21.06	19.42	19.85	19.78
Investment, $/kWh/day	416	340	260	192
Investment, $/gge/day	14142	11548	8833	6533

TABLE G.9 Low GHG Grid Case

	2010	2020	2035	2050
PHEV-10				
AEO base elec cost, $/kWh	0.096	0.112	0.126	0.148
Charger cost, $/car	849	748	598	448
Charger cost, $/kWh	0.066	0.058	0.047	0.035
Into LDV elec cost, $/kWh	0.162	0.170	0.173	0.183
AEO GHG, MMTCO_2	2516	1771	1270	648
WTT GHG kg CO_2/kWh	0.635	0.463	0.319	0.155
WTT GHG, kg CO_2/gge	21.21	15.48	10.67	5.17
Investment, $/kWh/day	362	319	255	191
Investment, $/gge/day	12317	10862	8679	6495
PHEV-15				
AEO base elec cost, $/kWh	0.096	0.112	0.126	0.148
Charger cost, $/car	849	748	598	448
Charger cost, $/kWh	0.048	0.042	0.034	0.025
Into LDV elec cost, $/kWh	0.144	0.130	0.126	0.119
AEO GHG, MMTCO_2	2516	1771	1270	648
WTT GHG kg CO_2/kWh	0.635	0.463	0.319	0.155
WTT GHG, kg CO_2/gge	21.21	15.48	10.67	5.17
Investment, $/kWh/day	260	230	183	137
Investment, $/gge/day	8853	7807	6238	4669
PHEV-20				
AEO base elec cost, $/kWh	0.096	0.112	0.126	0.148
Charger cost, $/car	849	748	598	448
Charger cost, $/kWh	0.038	0.034	0.027	0.020
Into LDV elec cost, $/kWh	0.134	0.122	0.119	0.114
AEO GHG, MMTCO_2	2516	1771	1270	648
WTT GHG kg CO_2/kWh	0.635	0.463	0.319	0.155
WTT GHG, kg CO_2/gge	21.21	15.48	10.67	5.17
Investment, $/kWh/day	208	184	147	110
Investment, $/gge/day	7082	6246	4990	3735
PHEV-30				
AEO base elec cost, $/kWh	0.096	0.112	0.126	0.148
Charger cost, $/car	4183	3411	2606	1926
Charger cost, $/kWh	0.139	0.113	0.087	0.064
Into LDV elec cost, $/kWh	0.235	0.201	0.179	0.158
AEO GHG, MMTCO_2	2516	1771	1270	648
WTT GHG kg CO_2/kWh	0.635	0.463	0.319	0.155
WTT GHG, kg CO_2/gge	21.21	15.48	10.67	5.17
Investment, $/kWh/day	760	620	474	350
Investment, $/gge/day	25854	21085	16111	11906
PHEV-40				
AEO base elec cost, $/kWh	0.096	0.112	0.126	0.148
Charger cost, $/car	4183	1967	1266	690
Charger cost, $/kWh	0.123	0.058	0.037	0.020
Into the LDV elec cost, $/kWh	0.219	0.170	0.163	0.168
AEO GHG, MMTCO_2	2516	1771	1270	648
WTT GHG kg CO_2/kWh	0.635	0.463	0.319	0.155
WTT GHG, kg CO_2/gge	21.21	15.48	10.67	5.17
Investment, $/kWh/day	673	549	419	310
Investment, $/gge/day	22888	18666	14262	10539
Battery Electric				
AEO base elec cost, $/kWh	0.096	0.112	0.126	0.148
Charger cost, $/car	4237	3460	2646	1957
Charger cost, $/kWh	0.076	0.062	0.047	0.035
Into the LDV elec cost, $/kWh	0.172	0.174	0.173	0.183
AEO GHG, MMTCO_2	2516	1771	1270	648
WTT GHG kg CO_2/kWh	0.635	0.463	0.319	0.155
WTT GHG, kg CO_2/gge	21.21	15.48	10.67	5.17
Investment, $/kWh/day	416	340	260	192
Investment, $/gge/day	14142	11548	8833	6533

Some utilities have noted the current on-board chargers in EVs limit power flow to about 3.3 kW. If, in the future, larger on-board chargers are used to reduce charging time (e.g., 8 to 15 kW), then the resultant energy flow would challenge the capacity of many residential power systems, even for a single charging installation, and for commercial building power systems where multiple charging stations were installed. This may require more extensive upgrading of the local distribution system, as well as building wiring changes. As a result, the utilities may charge increased fees beyond those covered by the cost of electricity. However, such costs are uncertain and difficult to quantify. The committee did not add additional investment costs in this category.

G.6.3 Additional Generation Capacity to Charge Electric Vehicles

The committee estimated the power on the grid required to fuel 100 million EVs in 2050 is about 286 billion kWh. If much of this charging is done off-peak, then a lesser amount of power is needed, and, as noted in chapter 3, depending on the region of the country, there may be considerable off-peak or reserve capacity. However, it is conservative to estimate the additional power and its cost on the basis that all of what is needed is new capacity. Furthermore, in the case of the AEO low-GHG grid case, the power growth from 2020 to 2050 is very low, probably inhibited by the high cost of electricity, which drives more efficient use of the installed generation sources. Hence, there is likely lower margin in the low-GHG grid and there may already be considerable off-peak use. Furthermore, the low-GHG grid does not assume a large use of electricity for transportation purposes. So the additional power generation capacity is estimated as being that which is added to the low-GHG grid case to charge 100 million EVs in 2050.

The average capacity factor for the new plants is assumed to be 0.4, since they will likely be a mix of gas plants with high-capacity factor and renewables with lower-capacity factor. For an additional generation capacity of 286,000,000 megawatt-hours, this translates to 90,000 MW of installed capacity. Assuming an average cost of $4,000,000 per megawatt, a total investment of $360 billion will be required. Some additional investment will be required to expand the high-voltage transmission system to carry this power to the load centers where it is further distributed by the lower-voltage distribution system. The total cost will be approximately $400 billion or more.

This capital cost is reflected in the cost of electricity to the customer and is not a separate cost. However, this large amount of capital will be needed to finance building the needed infrastructure as the generation expands as required to fuel the EVs. The utilities will recoup this cost plus a return on investment over a long period of time from the ratepayers.

G.6.4 Conversion of Existing Power Generation Sources to Low-GHG Emissions

Beyond the investment needed to provide the incremental power for EVs, there is an additional cost required to convert the existing grid to produce much lower emissions of GHGs, especially CO_2. This is because the grid does not preferentially transmit power from particular plants to specific loads. Even if sufficient capacity is added to the grid to produce the power for the EVs, and it is all low-GHG emitting, the full benefit of using EVs to reduce GHG emissions will not be achieved unless the whole grid has much lower GHG emissions on the average.

Table G.10 shows the generation mix for both the reference case and the low-GHG case in 2035. These data show there is a shift in the generation mix to reduce GHG emissions. The dominant changes are that coal, natural gas, and oil-fired sources of steam to produce electricity drop by about 130 gigawatt (GW) and about 180 GW of nuclear, renewable, and combined cycle natural gas generation are added. The low-GHG grid grows by about 35 GW from 2010 value (See Table 3.8 in Chapter 3 of the main report) so about 145 GW of new power is added for GHG reduction and as existing assets are retired. Assuming an average cost of $4 billion per GW for new capacity, the cost of the conversion is $500 billion to $600 billion through 2035.

TABLE G.10 2035 Net Summer Capacity and Electricity Production

Source	Reference Case Net Summer Capacity (GW)	Reference Electricity Production (Thousands GWhr)	Low GHG Case Net Summer Capacity (GW)	Low-GHG Electricity Production (Thousands GWhr)
Coal	317.9	2137.6	191.2	807.1
Oil and natural gas steam	88.7	124.7	84.4	123.8
Natural gas combined cycle	315.3	892.1	263.3	1203
Diesel/conventional combustion turbine	181.6	52.3	149.2	769
Nuclear	110.5	874.4	133.6	1052
Pumped storage	21.8	-0.1	21.8	-0.1
Renewables	148.5	547.6	204	737
Distributed generation	3.1	4.6	0.5	0.6
Total	1131.7	4633.2	1048.8	3976

Additional low-GHG generation sources must be added to the grid between 2035 and 2050, since the GHG emissions per kilowatt-hour of generation in 2050 needs to be about half that of 2035 to meet the 80 percent reduction goal in annual emissions. (See Table 3.8 in Chapter 3 of the main report.) Between 2035 and 2050 the low-GHG grid installed capacity is expected to grow by about 5 percent or 50-60 GW. Even if all this new capacity is low-GHG emissions, it is not sufficient to reduce the GHG emission by the desired amount. So more existing assets need to be retired or replaced and additional low-GHG emitting sources added. An amount will be needed that is comparable to the power sources added between 2010 and 2035. This suggests the total new capital needed to convert the U.S. electric power system to achieve an 80 percent reduction in annual GHG emissions by 2050 is of the order of $1 trillion.

G.7 THE USE OF NATURAL GAS TO POWER LIGHT-DUTY VEHICLES

Natural gas could contribute a significant portion of liquid fuels for light-duty vehicles (LDVs) in the United States by 2050 because it is a domestic, low-cost, and plentiful fuel with GHG emissions lower than petroleum-based fuels. However, the optimal mix of technologies for producing natural gas-based fuels is unclear. Issues include the cost of 1 gge in comparison with petroleum-based fuels, the need for any new fuel manufacturing and distribution infrastructure, the minimum economic increment of infrastructure investment, the availability and cost of vehicle technologies suitable for the particular fuel, and the life-cycle GHG emissions of the various natural gas-based fuel and vehicle technologies.

G.7.1 Advantages and Challenges of Each Pathway

G.7.1.1 Compressed Natural Gas for Direct Fueling

Advantages

- One gallon of gasoline equivalent of compressed natural gas (CNG) is cheaper than 1 gallon of petroleum-based gasoline.
- The technology is proven and available.
- Fuel distribution pipelines are in place and can supply initial requirements.

- Tailpipe emissions are much lower compared to petroleum-based gasoline.

Challenges

- CNG fuel stations are few and expensive to build.
- Dedicated CNG vehicles need to be designed (engines, trunk space, range).
- At low CNG LDV volumes and corresponding high CNG vehicle prices, and at the price differential between natural gas and gasoline observed in 2012, CNG vehicles are not economical.

G.7.1.2 Natural Gas for Electricity (PHEV and BEV)

Advantages

- Fuel cost per gallon of gasoline equivalent is low.
- There are no tailpipe emissions.
- Home charging stations can be sold at reasonable cost.
- Incremental capital investment into electricity infrastructure is minimal.

Challenges

- The batteries are expensive.
- Reasonably sized batteries provide short BEV range.
- PHEVs and BEVs are expensive.
- BEV batteries have long charging times.

G.7.1 3 Natural Gas to Liquid (Hydrocarbon) Fuels (Fischer-Tropsch and via Methanol-to-Gasoline)

Advantages

- Drop-in hydrocarbon fuels are produced.
- Distribution, dispensing, and vehicle infrastructure and technology are in place.
- Chemical process technology is proven.

Challenges

- Large investments in minimum incremental fuels plants create investment risk.
- Tailpipe emissions need to be controlled.
- GHG emissions are high relative to other alternative fuels.

G.7.1.4 Natural Gas to Methanol (“The Methanol Economy”)

Advantages

- Methanol is an excellent fuel in neat form or in low and high mixtures with gasoline.
- Minimal to no changes to engines required.
- Infrastructure for filling stations already exists.

- Life-cycle GHG emissions of natural gas to methanol is lower than those of petroleum-based gasoline.

Challenges

- Methanol has half the volumetric energy content of gasoline. The size of fuel tanks may need to be increased, depending on the mixing ratio of methanol and gasoline.
- Transdermal and inhalation toxicity debate needs to be settled.
- Movement and residence time in ground water debate needs to be settled.
- Methanol is corrosive to aluminum and certain plastic pipes and gaskets.

G.7.1.5 Natural Gas to Hydrogen

Advantages

- There are no tailpipe emissions.
- Hydrogen can be made from locally distributed natural gas without the need for a hydrogen pipeline infrastructure.
- Its initial introduction can rely on existing hydrogen supply chain.

Challenges

- Methane-to-hydrogen is more expensive than gasoline on a unit gallon of gasoline equivalent basis.
- Hydrogen pipeline infrastructure is necessary for large-scale use.
- Investment in hydrogen filling stations will be necessary.
- Vehicular hydrogen storage tanks are expensive.

G.7.2 Comparing the Efficiency of Different Options for Using Natural Gas as a LDV Fuel

Comparing these options can be difficult. However, a comparison based solely on use of the efficiency of energy in the gas removes many of the uncertainties. Such a comparison was made based on the vehicle fuel-utilization efficiencies of Chapter 2 and the fuel-conversion efficiencies of Chapter 3. The candidate vehicle propulsion systems include conventional internal combustion engines (ICEs) and advanced technologies such as EVs and FCEVs. Electric vehicles include conventional hybrid vehicles (HEVs), PHEVs, and BEVs. These vehicles differ in the size of the battery and electric motor compared with the ICE. An FCEVs also uses a battery and an electric motor, but replaces the ICE with a hydrogen fuel cell.

Table G.11 shows annual total natural gas usage if the entire LDV fleet was powered with conventional ICEs using natural gas as fuel from various pathways. The most efficient use of natural gas is direct use as CNG.

Table G.12 compares the annual natural gas usage if the entire LDV fleet were powered by electric or fuel-cell vehicles using natural gas as fuel via different pathways. These alternative vehicle technologies all require technology advances to be cost competitive with conventional ICEs.

At the beginning of the time period, efficiency favors the BEVs, but BEV technology is not technologically or economically competitive in the 2010-2030 time frame. (See Chapter 5.) By 2050, the efficiency of the propulsion technologies of HEVs, PHEVs, EVs, and FCEVs differ by less than 10 percent, which is within the uncertainty of the estimate. There is no clear winner based only on overall energy efficiency.

TABLE G.11 Total Natural Gas Usage If the Entire Light-Duty Vehicle Fleet Were to Be Powered by Conventional ICEs Using Natural Gas

	Total Natural Gas Usage, trillion cubic feet per year			
Year	Total Vehicle Miles Traveled (trillion)	Compressed Natural Gas	Drop-In Hydrocarbon Fuels	Methanol
2010	2.784	15.6	23.8	22.9
2030	3.727	10.1	15.5	14.9
2050	5.048	10.0	15.4	14.8

TABLE G.12 Comparison of Natural Gas Usage If the Entire Light-Duty Vehicle Fleet Were to Be Powered by Electric or Fuel-Cell Vehicles Using Natural Gas Via Different Pathways

	Total Natural Gas Usage, trillion cubic feet per year			
Year	Total Vehicle Miles Traveled (trillion)	HEV Powered by CNG and Gasoline	Full BEV	FCEV
2010	2.784	15.1	7.6	11.7
2030	3.727	8.4	7.5	7.3
2050	5.048	7.9	7.8	7.2

G.8 METHANOL AS A FUEL OR FUEL ADMIXTURE

Methanol as an automobile fuel has been used for years. Beyond decades of use in motor racing, methanol was used for 25 years by the public to drive about 200 million miles in California between 1980 and 2005. According to DOE's Energy Information Administration (EIA) (Joyce, 2012), methanol's decline might have been prompted in part by the occasional dramatic increases in natural gas prices, from which methanol is manufactured. Methanol is one of the alternative fuels being pursued in China.

Methanol is less volatile than gasoline, and, therefore, it is considered to have better fire safety. It can be mixed with gasoline by different proportions—it can be used as neat methanol, a mixture of 85 percent gasoline and 15 percent methanol (which may require no engine adjustment of a gasoline-powered ICE), or a mixture of 85 percent methanol and 15 percent gasoline. Methanol has a high octane number (114), and liquid methanol has a higher energy content (per volume) than liquid hydrogen. Methanol is made primarily from natural gas, but it can also be made from coal (both via syngas, CO, and H_2). With the abundant resources of natural gas and coal in the United States, methanol supply would be ensured. Methanol has about half of gasoline's volumetric energy content (2.01 gallon of methanol = 1 gge). Methanol prices in 2012 were less than \$0.50/gallon. Therefore, methanol would be an economically attractive alternative fuel or fuel additive. A "methanol economy" that includes methanol manufacture via the hydrogenation of sequestered CO_2 has been proposed (Olah et al., 2006).

So, why is the use of methanol as a fuel declining with an unsure prospect in the United States? Methanol has some of the same drawbacks as ethanol, and these can be managed the same way. Methanol is hygroscopic. It is a solvent for some plastics and corrodes aluminum, and, therefore, it is incompatible with some automotive tubing materials. The major concerns with methanol as an automobile fuel seem to be focused on environmental and health issues (see Malcolm Pirnie, 1999, for examples). Methanol is toxic, but the OSHA 40-hour exposure level of methanol (1,260 mg/m^3) is comparable to those of gasoline (900 mg/m^3) and ethanol (1,900 mg/m^3). There may be insufficient data about the health effects of inhaled and skin-penetrated methanol (while ingested methanol is well understood). There are conflicting data about the potential effects of spilled or leaked methanol on ground water (for example, its rate of penetration and half-life in the soil; Smith et al., 2003). Given the negative experiences with methyl tertiary butyl ether, concern has been raised about repeating those experiences with methanol.

With the recent emergence of plentiful and potentially cheap natural gas and, therefore, the potential for plentiful and cheap methanol, methanol will likely remain under consideration as an alternative fuel, probably prompting further studies of its environmental characteristics and health effects.

G.9 INFRASTRUCTURE AND IMPLEMENTATION FOR COMPRESSED NATURAL GAS AS AN AUTOMOBILE FUEL

G.9.1 Capital Costs of the Natural Gas Pipeline Infrastructure

The EIA forecasts show significant increases in future natural gas usage, albeit not for automotive use. From 2008 to 2035, the United States and Canada natural gas pipeline infrastructure has been projected to increase from a capacity of 26.8 trillion of standard cubic feet per year to 31.8 to 36 trillion of standard cubic feet per year (EIA, 2011). The corresponding investment will be $133 billion to $210 billion, divided between transmission (80 to 83 percent), storage (1 percent), gathering (7 to 8 percent), processing (7 to 8 percent), and liquefied natural gas (1 percent). These projections are for the combined U.S. and Canadian infrastructure. About 12 percent of the natural gas consumed in the United States in 2009 was imported from Canada, and thus Canada has part of the natural gas pipeline infrastructure required to supply the U.S. consumption. In a report addressing the same issues, ICF International (2009) concluded that between 2009 and 2030, the United States and Canada will need 28,900 to 61,000 miles of additional natural gas pipeline and 371 to 598 billion cubic feet (bcf) additional storage capacity to satisfy projected natural gas market requirements. None of these projections appear to account for any significant increase in natural gas use for automobile transportation. Because of the low projected volumes of natural gas used in transportation during this time period, the growth of the CNG fleet is unlikely to be limited by pipeline infrastructure for natural gas, as already mentioned before.

G.9.2 CNG Filling Station Capital Costs

As of February 2010, the United States had 247 million registered road vehicles (136 million cars, 110 million trucks, and 1 million buses). These were served by 159,006 “retail gasoline outlets” (gas stations) at a ratio of 1,553 vehicles/gas station. As of 2010, the global ratio of natural gas vehicles to filling stations was 685 vehicles per station (Pike Research, 2011). At the same time, the United States had a total of 1,327 natural gas filling stations (private and public-access combined). Only 60 of the stations were for LNG, and the majority was for CNG. The economic difficulties in building a dispensing infrastructure for natural gas are illustrated by the fact that these 1,327 natural gas filling stations in the United States serve only a total of 112,000 vehicles in the country, for a ratio of 84 natural gas vehicles per filling station. This is most likely an uneconomically small ratio for an independent, for-profit, public-access natural gas filling station. For 2016, Pike Research (2011) forecasted that the number natural gas vehicles will increase at a rate of 8 percent per year, while the number of natural gas filling stations will increase only at 5 percent per year.

There are four types of natural gas filling station designs: time filling (mostly for home use, 8 hours), cascade fast-fill (public access, with natural gas storage), central fast-fill (buffered, for large vehicles), and combined CNG/LNG stations. Natural gas filling station costs have been discussed by the DOE’s Idaho National Laboratory (INL, 2005). For storage and dispensing equipment only (no buildings and land), LNG stations were estimated to cost $0.35 million to $1 million, in comparison for gasoline-station equipment at $0.15 million. It appears that CNG filling stations will be fairly modular so that their cost will likely scale somewhat linearly with dispensing capacity.

An investment opportunity for CNG filling stations was published recently on the Internet (International CNG, 2012). It suggested that a $1.75 million investment is needed into a CNG station located in the District of Columbia, Maryland, or Virginia. A station would serve 1,000 cars per week, 10 gge/fill/car/week, with $0.50 margin over the cost of natural gas for a 15 percent return on investment.

The natural gas filling station infrastructure costs can be estimated based on the above investment offer by assuming one filling station per 1,000 CNG vehicles and a cost of $1.3 million per filling station (land, buildings, and equipment). On that basis, for example, for 5 million CNG vehicles, the filling station infrastructure would cost about $6.5 billion. CNG compressing and dispensing equipment is being sold by the clean-energy company IMW Industries at the writing of this report.

For municipal CNG vehicle fleets, the National Renewable Energy Laboratory report (Johnson, 2010) analyzes the business case for filling stations. A model has been developed that allows an investor to compute capital requirements and returns as a function of a number of equipment and operating variables.

The price of home-dispensed CNG can be significantly lower than filling station-dispensed CNG. As a result, CNG vehicle owners have been interested in home refueling. Honda Civic GX owners in California were able to purchase a home-fill station for overnight refueling for about $4,500 and have it installed at an additional fee. As of this writing, Honda is not recommending the home refueling of their CNG vehicles, due in part to concerns about the humidity content of home natural gas.

G.10 REFERENCES

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H

Modeling

H.1 MODELING THE TRANSITION TO ALTERNATIVE FUELS AND VEHICLES USING VISION

H.1.1 The VISION Model

The VISION model was developed by Argonne National Laboratory as a means of extending the transportation sector component of the Energy Information Adminstration's (EIA's) National Energy Modeling System (NEMS) model to longer-term projections of U.S. energy use and greenhouse gas (GHG) emissions. The model is available to the public as a downloadable Excel file and is updated each year to incorporate recent results from NEMS and the EIA *Annual Energy Outlook* (AEO) report.[1] VISION calculates energy use and greenhouse gas emissions for light, medium, and heavy-duty vehicles using simple algebraic energy balance equations and input assumptions about vehicle fleet mix, efficiency of vehicles, fuel characteristics, and vehicle miles traveled (VMT) out to the year 2050 and beyond. Although the calculations are conceptually simple, the model is complicated in that it incorporates a wide range of data and conversion factors to explicitly track multiple vehicle vintages, fuel types, and other trends on an annual basis. Singh et al. (2003) and Ward (2008) provide documentation and a user's guide for the VISION model.

VISION does not include any market feedback effects over time within the model or between the transportation sector and other sectors of the economy.[2] Fuel and vehicle prices are exogenous to the model and must be specified by the user. Any responses to changes in those prices would also have to be specified by the user. So, if, for example, deployment of more efficient vehicles in the VISION model reduces demand for petroleum fuels, there is no feedback to the global petroleum market and subsequent changes to gasoline and diesel fuel prices. Default values in VISION are calibrated to transportation sector results from the NEMS model, which does account for interactions between global and domestic energy markets. What VISION can assess are the effects on energy use and GHGs when there are different shares of vehicle types and fuel types over time. Vehicle shares, efficiencies, fuel volume constraints, and fuel intensities are the major inputs to the model. VISION uses the GREET 1-2011 model for assumptions about the GHG emissions rates of different fuels,[3] but the analysis in this study relies on the judgment of the committee for GHG intensity rates.

VISION was used to explore the range of possible vehicle and fuel combinations that could attain the goals of this study and their associated costs. The committee modified VISION in a number of ways to add capability for the purposes of this study. The revised VISION model, referred to here as the VISION-NRC model, includes the most up-to-date assumptions from the committee about vehicle efficiencies, fuel availability, and GHG emissions of specific fuels. The sections below review the scenarios developed for the committee using VISION-National Research Council (NRC) (Section H.1.2)

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[1] See http://www.transportation.anl.gov/modeling_simulation/VISION/.

[2] VISION does include a demand elasticity function to adjust VMT in response to fuel price change assumption; however, this function was not used in the present study.

[3] Features of GREET1_2011 are listed at http://greet.es.anl.gov/.

and major modifications made to the original VISION model in developing VISION-NRC (Section H.1.3). For more information on the VISION model and to download the model itself, see the attached Appendix H VISION Model Spreadsheet.

H.1.2 VISION-NRC Scenarios

To explore possible paths to attain the goals, VISION-NRC was run for a range of cases. The predominant characteristic of these runs was to focus on a market dominated by a particular vehicle type and alternative fuel (i.e., battery electric vehicles (BEVs), fuel-cell vehicles). To assess the range of possibilities, the committee looked both at runs that used the midrange vehicle efficiencies for these advanced vehicles as well as runs that used the optimistic efficiencies to represent technological breakthroughs, as described in Chapter 2 and summarized in Table 2.11. From the fuels side, the committee considered both business-as-usual (BAU) production of a fuel (gasoline, hydrogen, or electricity) as well as a low-GHG fuel supply technologies, as described in Chapter 3 (low-net-GHG biofuels, H_2 generation with carbon capture and storage (CCS), or a low-GHG electric grid).

Some of the key assumptions throughout all of the runs are listed below.

- There are two “reference cases” in the committee’s analysis. There is the BAU Case, which is basically the AEO 2011 assumptions, and then there is the Committee Reference Case, which includes, instead of the AEO assumptions, all of the committee assumptions about vehicle efficiencies, fuel carbon intensity, and effects in the future of existing regulations (see below).
- All runs of the model, except the AEO BAU Case, use the committee’s assumptions on vehicle efficiencies, GHG impact of the fuels supplied, and availability of resources. Committee estimates of vehicle fuel efficiencies can be found in Table 2.12 of Chapter 2.
- Total new vehicle sales each year are drawn from the AEO 2011 Reference Case and do not change with the different runs, only the mix of vehicles changes; VMT per vehicle is from AEO Reference Case forecast and falls over time as vehicles age; total VMT of the fleet is the same for each run and is consistent with the AEO 2011 assumptions about total VMT over time (see Table H.1).
- Oil prices are taken from AEO 2011 and are expected to gradually increase to $125/barrel by 2035, resulting in a pre-tax gasoline price of $3.16 in that year. Gasoline prices are then extrapolated out to 2050, assuming the compound rate of growth modeled in AEO 2011 from 2030-2035. The current gasoline tax of $0.42/gallon is assumed to hold true out to 2050.
- VMT per year for battery electric vehicles (BEVs) are assumed to be two-thirds that of other vehicles, due to battery range limitations.
- The shares of new vehicles sales by type of vehicle (hybrid electric vehicle [HEV], plug-in hybrid electric vehicle [PHEV[4]], fuel cell electric vehicle [FCEV], etc.) are from AEO Reference Case for our BAU run; for the committee scenarios, shares are assumed to change as specified in Table H.1. In the scenarios where alternative vehicles are assumed to enter the fleet in large numbers, it is assumed that new vehicle shares never increase by more than 5 percentage points of the new vehicle stock in any given year.
- Only one PHEV, a PHEV-30, with a real world all-electric driving range of 25 miles—this yields a utility factor of 46 percent is included.
- GHGs from biofuels include both direct emissions from production and also emissions from indirect effects on land use (see Chapter 3).

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[4] BEVs and PHEVs are collectively known as plug-in vehicles (PEVs).

TABLE H.1 Assumptions Taken from AEO 2011; These Hold for All VISION Cases

	2005	2030	2050
Total LDV sales, 1000s/year	16,766	18,502	22,219
Stock of LDVs, millions	234.6	282.2	365.2
Share of cars, percent of total fleet			
Total VMT, trillion VMT	2.69	3.76	5.05
Average VMT,[a] VMT/LDV	11,455	13,316	13,822

[a] Average VMT is assumed to two-thirds of this for BEVs.

A detailed overview of the different VISION cases is provided below, with Table H.2 summarizing the differences. For more information on fuel efficiency assumptions of vehicles, see Table 2.12. For more information on the carbon rates of different fuels, see Table 3.4 in Chapter 3.

- *AEO BAU Case.* Uses AEO 2011 Reference Case assumptions on VMT, vehicle shares, vehicle efficiencies, fuels shares, and fuel GHG impacts. AEO forecast only is made to 2035. VMT was extrapolated to 2050 assuming a 1.5 percent growth rate from 2036 to 2050. Corporate Average Fuel Economy (CAFE) standards are only assumed to be specified through the 2016 model year, but not beyond. This case assumes a small amount of coal to liquid (CTL) fuel and gas to liquid (GTL) fuel is introduced by 2035.
- *Committee Reference Case.* The Committee defines its own reference case that includes all of the midrange assumptions about vehicle efficiencies, fuel availability, and GHG impact developed by the committee (summarized in Chapters 2 and 3). In addition, this case assumes that the recently finalized 2025 CAFE and GHG standards for fuel efficiency of light-duty vehicles (LDVs) will be met, and the standards will then stay at that level through 2050. The standards are interpreted to require that new vehicles in 2025 must have on-road fuel economy averaging about 41 mpg (given a fleetwide CAFE rating of 49.6 mpg). New vehicle sales shares are adjusted to meet this standard—primarily, advanced internal combustion engine vehicle (ICEV) and HEV shares are increased. After 2025, there is a very small annual improvement in average fuel consumption (~0.3 percent), which is consistent with the AEO2011 projection. This case also assumes that the federal Renewable Fuels Standard (RFS2) will be met by 2030. As a result, corn ethanol sales rise to about 10 billion gallon of gasoline equivalent (gge) per year by 2015 and stay at that level through the period. And, based on the analysis in Chapter 3, it is assumed that all cellulosic biofuels will be thermo-chemically derived drop-in fuels. The RFS2 requirements result in production of 14 billion gge per year of such biofuels by 2030, and it is assumed that they remain roughly constant after that time.
- *Emphasis on ICE Vehicle Efficiency.* A set of model runs that continue the focus on light duty fuel efficiency improvements through the period to 2050. Shares of advanced ICEVs and HEVs increase to just over 80 percent of new vehicles by 2050. Two runs are included that differ only in their assumptions about the fuel efficiency improvements of vehicles over time. The first assumes the midrange assumptions for fuel efficiency for all technologies (Chapter 2, Table 2.12), and the second assumes optimistic fuel efficiency for ICEs and HEVs, while maintaining midrange values for the small numbers of other types of vehicles in the fleet. It is assumed that the RFS2 requirements described above (under the Committee Reference Case) are still in place, bringing in some corn ethanol and cellulosic biofuels. These increased vehicle efficiency cases require much less liquid fuel over time, and it is assumed that the fuel backed out is gasoline.
- *Emphasis on ICE Vehicle Efficiency and Biofuels.* Two runs are similar to the Committee Reference Case and the emphasis on efficiency case, with the difference that more biofuels are brought into the market after 2030. The amount of biofuel brought to the market rises to the limit specified by the

committee in Chapter 3, which is 45 billion gge/year and assumes 703 million dry tons per year of cellulosic feedstock. The two runs of the model both assume this additional biofuel, largely in the form of drop-in gasoline components that displace petroleum, and the difference in the two runs is just the assumption on the fuel efficiency of vehicles. As in the case above, the first run assumes all vehicles are at the midrange efficiency. In this run, the share of petroleum-based gasoline as a liquid fuel falls to about 25 percent by 2050. The second run assumes optimistic fuel efficiency for ICEVs and HEVs. In this case, bio-based ethanol, bio-based gasoline, and a small amount of CTL and GTL, make up all liquid fuel, with almost no petroleum-based gasoline.

- *Emphasis on fuel cell vehicles.* This case also has four different runs of VISION to capture variation in both vehicle efficiency and fuel carbon content. In all of these runs, the share of fuel cell vehicles (FCVs) increases to about 25 percent of new car sales by 2030 and then to 80 percent by 2050, modeled on the maximum practical deployment scenario from *Transition to Alternative Transportation Technologies: A Focus on Hydrogen* (NRC, 2008). There are two runs with the midrange vehicle fuel efficiencies, each with a different assumption about the GHG impact of the hydrogen production. Finally, there are two additional runs with optimistic assumptions about the fuel efficiency of FCVs, each with the different assumptions for the GHG emissions from hydrogen production. The hydrogen produced from a mix of low-GHG-emitting sources is assumed to come from production facilities, because they might operate under a sufficiently high carbon price. The CO_2 emissions are about one-fifth of those from the alternative, low-cost hydrogen fuel generation (2.6 g CO_2e/gge H_2 compared to 12.2 g CO_2e/gge H_2; see Table 3.15).
- *Emphasis on electric vehicles.* There are four VISION runs for this case that account for differences in assumptions about vehicle efficiency as well as the GHG emissions of the fuel. It is assumed in all runs that the share of BEVs and PHEVs increases to about 35 percent of new car sales by 2030 and 80 percent of new car sales by 2050, in line with the rates put forth in *Transitions to Alternative Transportation Technologies: Plug-In Hybrid Electric Vehicles* (NRC, 2010), and this case assumes relatively greater sales of PHEVs than BEVs in all years. The first two runs assume midrange vehicle efficiency, each with a different assumption about GHG emissions from the electricity grid. These forecasts for the make-up of the grid are derived from the two cases put forth in AEO 2011 (EIA, 2011). The first is the BAU Case, and the second is the GHG price economy-wide case, where a low-GHG emissions grid is achieved by a tax on carbon that is first assessed in 2013 and increases at 5 percent per year (further details of the two grid scenarios can be found in Chapter 3). The second set of runs both use the optimistic assumptions about vehicle efficiency for the BEVs and PHEVs, again, with the two differing only in their assumptions about the GHG emissions from the grid. The low-GHG emissions grid is assumed to emit 111 g CO_2 per kWh of generated power by 2050, reduced to just 21 percent of the BAU grid (541 gCO_2e/kWh; see Table 3.8 and discussion).
- *Emphasis on natural gas vehicles.* This case has a set of runs that assumes an increasing penetration of compressed natural gas (CNG) vehicles into the market. The new car sales of CNG vehicles are assumed to be 25 percent by 2030 and 80 percent by 2050, as in the case for HFCVs due to a comparable level of current technological deployment. In the first run, the committee assumed that all vehicles attain the midrange efficiencies. The second run assumes optimistic fuel efficiency for CNG vehicles and midrange for the other vehicles in the fleet. CNG fuels rise over time to fuel the vehicles, and very little liquid fuel is needed by 2050. The committee continued to assume that RFS2 must be met by 2030, so the liquid fuel that is used is primarily biofuels in both of these runs. So little liquid fuels are needed in these runs that the committee assumed no CTL and GTL comes into the market—the plants are never built. CO_2 levels are about 82 percent of conventional gasoline, on an energy basis (gCO_2e/MJ, see Chapter 3).

TABLE H.2 VISION Run Assumptions

Cases	Vehicle Efficiencies	Fuel Assumptions	Shares of New Vehicles
AEO BAU	AEO assumptions	AEO 2011	AEO assumptions
Committee Reference Case	Midrange	Committee assumptions, TCC biofuel available 13 bgge/year by 2030	Small increase in HEVs above AEO in order to meet CAFE
Emphasis on ICE Vehicle Efficiency	1. Midrange all vehicles 2. Optimistic for ICEs, HEVs, midrange others	1. Reference 2. Emphasis on biofuels, thermochemical conversion increases to 45 bgge/year by 2050	90% HEV share by 2050
Emphasis on Fuel Cells/Hydrogen	1. Midrange all vehicles 2. Optimistic for FCVs	1. Low cost hydrogen 2. Low-CO_2 hydrogen	25% HFCVs in 2030 80% HFCVs in 2050
Emphasis on Electric Vehicles	1. Midrange all 2. Optimistic PHEV, BEV	1. AEO 2011 grid 2. Low-CO_2 grid	35% PEVs in 2030 80% PEVs in 2050
Emphasis on Natural Gas ICEVs	1. Midrange 2. Optimistic	Committee assumptions	25% CNGVs in 2030 80% CNGVs in 2050

H.1.3 Major Changes to the Original Vision Model to Develop VISION-NRC

The VISION-NRC model was developed from the “VISION_2010_AEO_Base_Case” version of the VISION model, which includes EIA’s AEO 2010 projections to 2035 and GHG and upstream energy use rates from GREET 1.8d.1. The sections below review the major modifications made to this original Excel model to develop the VISION-NRC model.

H.1.3.1 Changes to the Model Input Sheet

The Model Input worksheet has been modified to store multiple scenario assumptions. Sets of inputs can be changed for each scenario by changing the value of the “CS” named variable, located in cell B5. Alternates of each scenario can be chosen by changing the values in cells I9:I12. The actual input values for each scenario are provided in the columns to the right of the main input columns, columns A through N. This is also where the scenario values themselves can be modified, though changes in one parameter can influence the implications of other parameters. For example, if fuel economy or VMT assumptions are changed, the fuel split parameters, expressed in percentages of total fuel (such as percent of ethanol as corn ethanol), would need to be modified to maintain the same absolute volume of a particular fuel type.

H.1.3.2 Updates to AEO 2011 Data

Key model inputs were updated to the revised data used in the VISION-2011 AEO BAU Case model. These are indicated in the Auto-LTs worksheet and include the following: annual auto and light truck sales, LDV stock values, and baseline new vehicle miles per gallon gasoline equivalent values.

TABLE H.3 Data for Baseline GHG Emissions to Which 2050 Levels Are Compared

2005 Metrics	Units	AEO 2007 2005, All LDVs	Source
Energy Use (HHV)	trillion Btu	16,227	AEO 2007, Table 35, Transportation Sector Energy Use by Mode
	bgge (LHV)	139.89	Total Energy use converted to gallon gasoline equivalents
Vehicle Miles Traveled	million miles	2,687,058	AEO 2007, Table 50, LDV Miles Traveled by Tech. Type
Average mpg	mpgge	19.21	Calculated as total VMT / Total Energy
Average FCI	gCO2e/MJ	94.73	Calculated from fuel energy and FCI values below
Greenhouse gas emissions	MMTCO2e	1,514.23	Calculated as Total Energy × Average FCI
Energy Use by Fuel Type			
Motor Gasoline	bgge	123.76	AEO 2007, Table 36, Transportation Sector Energy Use by Mode
Ethanol	bgge	4.77	Includes 4.757 BGGEs, and subtracted from above
Compressed Natural Gas	bgge	0.06	Same as above
Liquefied Petroleum Gases	bgge	0.04	Same as above
Electricity	bgge	0.01	Same as above
Distillate Fuel Oil (diesel)	bgge	1.99	Same as above
Total	bgge	130.61	Same as above
Fuel Carbon Intensity (FCI, LHV)			
Motor Gasoline	gCO2e/MJ	91.27	NRC Fuels Committee (2010 FCI Value)
Ethanol	gCO2e/MJ	44.63	NRC Fuels Committee (2010 FCI Value)
Compressed Natural Gas	gCO2e/MJ	74.88	NRC Fuels Committee (2010 FCI Value)
Liquefied Petroleum Gases	gCO2e/MJ	79.48	GREET value from VISION model
Electricity	gCO2e/MJ	165.25	NRC Fuels Committee (2010 FCI Value)
Distillate Fuel Oil (diesel)	gCO2e/MJ	90.04	NRC Fuels Committee (2010 FCI Value)
Average FCI	gCO2e/MJ	94.73	Calculated as fuel energy-weighted average
Greenhouse Gas Emissions			
Motor Gasoline	MMTCO2e	1,382.41	
Ethanol	MMTCO2e	26.03	
Compressed Natural Gas	MMTCO2e	0.51	
Liquefied Petroleum Gases	MMTCO2e	0.40	
Electricity	MMTCO2e	0.11	
Distillate Fuel Oil (diesel)	MMTCO2e	21.89	
iLUC from ethanol production	MMTCO2e	82.88	
Total	MMTCO2e	1,514.23	
Conversion Factors			
Btu/gal gasoline (HHV)		124,238	AER 2010, Table A3 p367, 2005 value
Btu/gal gasoline (LHV)		116,000	NRC Fuels Committee
Btu/MJ		947.8	

H.1.3.3 The New “NRC Results” Sheet

Key output values and graphs are located in a new tab, “NRC Results,” and the values for most of these graphs are contained in the columns to the right of the graphs themselves.

H.1.3.4 Calibrating the 2005 GHG Baseline

Table H.3 summarizes data used to determine the baseline GHG emissions in 2005.

H.1.3.5 Changes to the LDV Stock Sheets

The vehicle stock sheets for each vehicle type have been modified to incorporate various scenario assumptions. For example, VMT for BEVs can be adjusted downwards and redistributed to other vehicle types in the revised stock sheets (see explanation below). In addition, new correction factors have been incorporated and fuel carbon intensity values have been linked directed to the stock sheets in a new column.

H.1.3.6 Changes to the Carbon Coefficients Sheet

The Carbon Coefficients worksheet has been modified to incorporate the unique fuel carbon intensity values used in the scenarios. Calculations to capture the accounting used for indirect land use change (iLUC) emissions are also included in this worksheet.

H.1.3.7 Calculation of iLUC GHG Emissions as a Result of Increased Biofuels Production

The additional GHG emissions associated with expanding biofuels production, due to iLUC, is calculated as a function of new production capacity established in any given year:

$$GHG_{iLUC} = Q_{new} \times F_{fuel}$$

Where new production capacity, Q_{new}, has units of bgge/year, and the emissions factor for a particular fuel, F_{fuel}, has units of MMTCe /(bgge/year). For corn ethanol, $F_{CornEthanol}$ = 29.9 MMTCe/(bgge/year), and for thermochemical biofuels, $F_{Thermochem}$ = 15.3 MMTCe/(bgge/year). These values are determined from committee data in the Carbon Coefficients worksheet, and then added to the total GHG emissions in the NRC Results worksheet. In years where no new production capacity is installed, no additional iLUC GHGs are emitted.

H.1.3.8 Redistribution of BEV VMT to Remainder of LDV Fleet

It is estimated that 33 percent of the BEV VMT that would have been driven are redistributed to all other LDV cars or light trucks, using Equation H.1.

$$VMT_{i,n} = VMT_{i,n}^{o} + \frac{N_{i,n}}{N_{Total\,Cars\,or\,L.Trucks,n}}\left(\frac{1}{3}VMT_{i=BEV,n}\right) \qquad \text{(H.1)}$$

Where i = vehicle type (ICE, PHEV, etc.) and n = year.

The equation applies for cars and light trucks separately. In other words, for i = ICE, the ratio of ICE cars in year n ($N_{ICE,n}$) to total cars (N_{cars}) would be multiplied to one-third of VMT from BEV cars in year n ($VMTi = BEV,n$).

This equation can be interpreted as an equal distribution of all “displaced” BEV car or light truck VMT (from any vintage) across all cars or all light trucks (of any vintage). Note that in VISION fuel use is determined by multiplying total VMT for any platform type (e.g., BEV cars) to the VMT-weighted fuel economy of all vehicles (of all vintages, which have distinct VMT/year) on the road. In the calculation, it is just the total VMT that increases proportional to the percent of cars or light trucks on the road.

Another way of calculating this redistribution might be to allocate proportional to the VMT of any platform type divided by all VMT by cars or light trucks. With scenarios that have newer vehicles being much higher fuel economy than older vehicles, this approach would result in lower fuel demand than distributing by the percent of total on-road vehicles. However, this approach implies BEV VMT would tend to be preferentially transferred to newer vehicles (which have higher VMT/year) compared to older vehicles (with lower VMT/year, as older vehicles are driven less). This allocation seems less realistic, considering that households purchasing a new BEV would probably not also have a new LDV of another type.

Conceivably, an algorithm could be developed to determine the degree to which VMT would tend to be transferred to vehicles of a different vintage than the on-road fleet average vintage. In theory, for example, a household purchasing a BEV may not necessarily have a second or third vehicle with a vintage equal to the fleet average. It may be more wealthy households with second vehicles slightly newer than the fleet average. Given that BEVs will be introduced into the LDV fleet gradually over time, and that newer more efficient vehicles would mostly likely also be achieving greater market share over the same period, the effort of differentiating VMT distribution more realistically by vintage would likely result in a small change in fuel use compared to the vehicle share allocation described above.

H.2 LIGHT-DUTY ALTERNATIVE VEHICLE ENERGY TRANSITIONS MODEL: WORKING DOCUMENTATION AND USER'S GUIDE

The Light-Duty Alternative Vehicle Energy Transitions (LAVE-Trans) Model described in this section was developed by David L. Greene, Oak Ridge National Laboratory and University of Tennessee; Changzheng Liu, Oak Ridge National Laboratory; and Sangsoo Park, University of Tennessee. The committee agreed by consensus to use this model for its analysis. See the attached Appendix H LAVE-Trans Model Spreadsheet.

H.2.1 Purpose

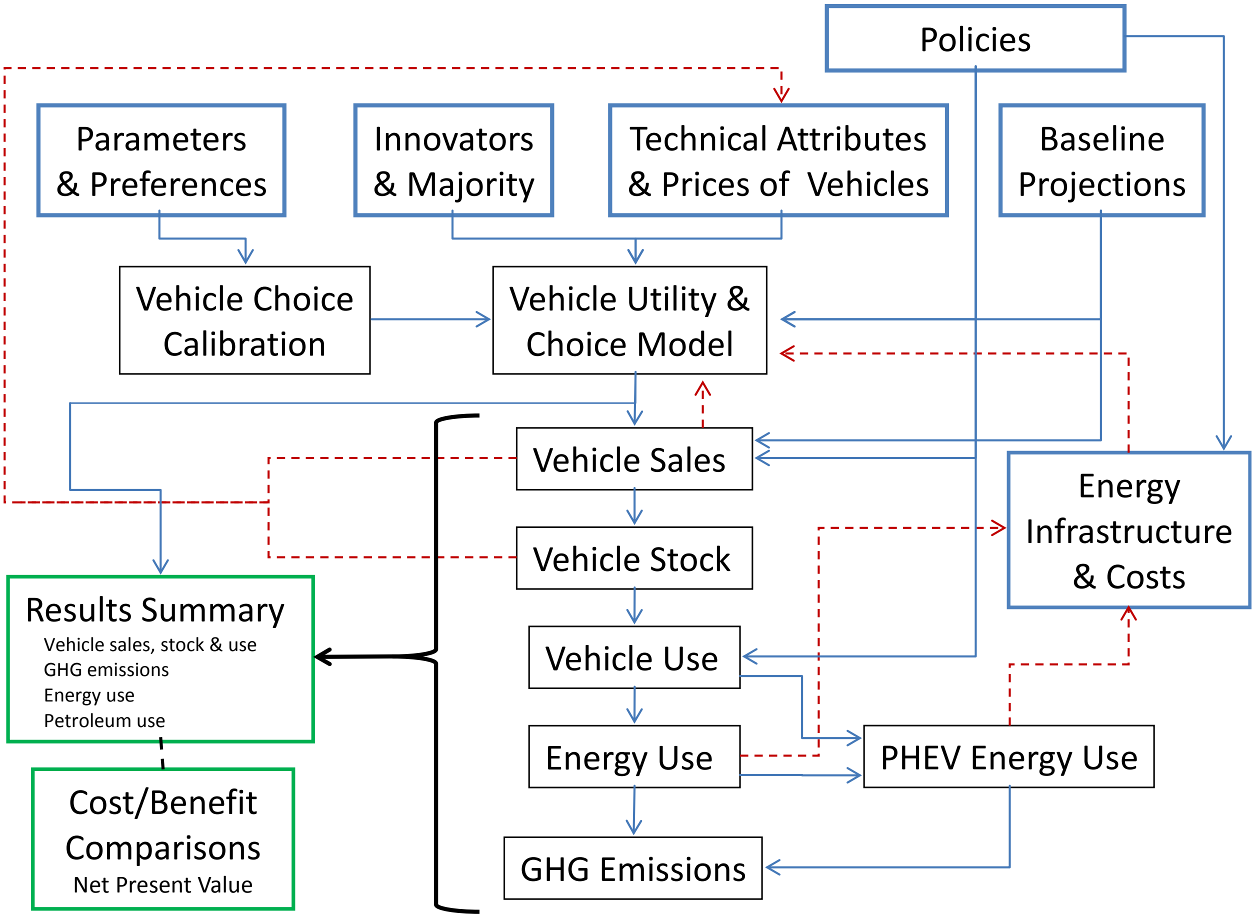
The transition from a motor vehicle transportation system based on ICEs powered by fossil petroleum to low-GHG-emission vehicles poses an extraordinary problem for public policy. The chief benefits sought are public goods: environmental protection, energy security, and sustainability. As a consequence, market forces alone cannot be relied on to drive the transition. Securing these benefits may require replacing a conventional vehicle technology that has been “locked-in” by a century of innovation and adaptation with an enormous infrastructure of physical and human capital. The time constants for transforming the energy basis of vehicular transport are reckoned in decades rather than years. A comprehensive, rigorous, and durable policy framework is needed to guide the transition.

The LAVE-Trans model was developed to quantify the private and public benefits and costs of transitions to electric drive vehicles under a variety of future scenarios, making use of the best available information in a rigorous mathematical framework. At present, knowledge of the key factors affecting LDV energy transitions is incomplete. As a consequence, the model's outputs should not be considered accurate predictions of how the market will evolve. Rather, the LAVE-Trans model provides a framework for integrating available knowledge with plausible assumptions and analyzing the implications for benefits, costs and public policies.

The transition to electric drive vehicles faces the following six major economic barriers that help to lock in petroleum-powered vehicles:

1. Technological limitations,
2. The need to accomplish learning by doing,
3. The need to achieve scale economies,
4. Consumers' aversion to the risk of novel products,
5. Lack of diversity of choice, and
6. Lack of an energy supply infrastructure.

Each of the six barriers can be viewed either as a transition cost or as a positive external benefit created by adoption of the novel technology. Modern economics recognizes “network externalities,” positive external benefits that one user of a commodity can produce for another. Each of these barriers has been incorporated in the model so that the costs of overcoming them, and alternatively the external benefits of policies that break them down, can be measured, subject to the limits of current knowledge.



All feedback loops are recursive rather than simultaneous and are indicated by a dashed red line ---

FIGURE H.1 Diagrammatic representation of the LAVE-Trans Model.

This report provides an overview of the LAVE-Trans model structure, explains how it functions, and provides instructions for operating it. Section H.2.2 provides an overview of the model structure and the components and how they are linked together. Section H.2.3 describes each component, including the key equations that control its operation. Section H.2.4 describes the inputs (parameters and data) that must be supplied to the model, and Section H.2.5 describes model outputs. Section H.2.6 is a brief users' guide to executing a model run.

H.2.2 Model Structure

The LAVE-Trans model is an Excel spreadsheet model comprised of 25 worksheets. Figure H.1 illustrates the relationships between the major components of the model. The areas where exogenous inputs enter the model are shown as blue boxes. A relatively large amount of exogenous information is required to carry out a model run. Baseline projections of vehicle sales and energy prices are required to 2050. Technical attributes of advanced technology vehicles, including fuel consumption per kilometer, on-board energy storage, and retail price equivalent (RPE) at full scale and learning, must be specified for current and certain future years. Parameters that describe consumers' willingness to pay for vehicles and their attributes must also be provided. The model translates these into coefficients for the vehicle choice model. Capital, operating, and input costs of both electric, hydrogen, and natural gas infrastructure or alternative price projections must also be provided.

The model can be automatically calibrated to specified vehicle sales and vehicle use projections. At that point the Vehicle Choice model estimates the shares of ICE, HEV, PHEV, BEV, and FCV or CNG technologies for passenger cars and light trucks and for Innovator and Majority market segments. The market shares are multiplied by the passenger car and light truck sales totals in the Vehicle Sales worksheet. Sales are passed to the Vehicle Stock worksheet, which retires vehicles as they age and keeps track of the number of vehicles of each technology type by model year for every forecast year. Vehicle kilometers by age and vehicle type are calculated in the Vehicle Use worksheet. In the Energy Use worksheet, energy use is calculated for all but PHEVs by multiplying vehicle kilometers by the number of vehicles and by on-road energy consumption per kilometer. PHEV energy use, electricity and gasoline, is calculated in a separate worksheet. GHG emissions factors are applied to energy use in the GHG Emissions worksheet.

In a BAU run, the total passenger car and total light truck sales will exactly match the input projections. The technology and price assumptions of the BAU Case should match the baseline projection to which the model's vehicle sales and vehicle use have been calibrated. Next, a Base Case, reflecting alternative technology and price assumptions can be run. In the Base Case, vehicle sales, vehicle use, energy use, and GHG emissions will change due to the new technology and price assumptions. Once a Base Case run has been made, it is transferred to the Base Case worksheet by clicking on a button in the Current Case worksheet. A policy run may then be created by specifying vehicle or fuel subsidies or taxes, exogenous investments in fuel infrastructure, or by changing assumptions about vehicle or fuel technologies. In a policy run, sales may be higher or lower than the Base Case, depending on the specific policy assumptions. The results of a policy case are stored in a Current Case worksheet, which also contains built-in graphical displays. The impacts of the Current Case relative to the Base Case are calculated in the Costs-Benefits worksheet. A standard set of tables and graphs summarizing the BAU Case, Base Case, and Current Case are stored in an Output worksheet.

There are several important feedback loops in the model. Feedbacks are recursive (with a 1-year lag) rather than simultaneous. This simplifies the solution of the model greatly but is also generally more representative of how changes can be made in the motor vehicle industry. Cumulative vehicle sales generate learning-by-doing effects that lower vehicle prices over time. Sales are accumulated in the Vehicle Sales worksheet, and learning effects are calculated there, as well. Current sales affect the availability of different makes and models, i.e., the diversity of choice available for both advanced and conventional ICE technologies. A diversity of choice metric is passed to the Vehicle Attributes worksheet. Current sales also affect next year's vehicle prices via scale effects, also computed in the Vehicle Sales worksheet. Both learning and scale effects are passed to the Vehicle Production worksheet, where RPEs are calculated for each technology in each future year. These adjusted prices are then passed to the Vehicle Attributes worksheet.

Demand for electricity, hydrogen, and natural gas, plus exogenous assumptions about the supply of refueling/recharging infrastructure, are passed to the Fuel Input worksheet, where the quantities and costs of infrastructure are calculated. For hydrogen, these costs also depend on the model user's assumptions about how hydrogen will be produced and delivered to vehicles in the future. These assumptions also affect the cost of hydrogen and its GHG emissions per kilogram. The availability of refueling/recharging infrastructure is passed to the Vehicle Attributes model and influences the choice among alternative technologies.

The following is a list of the model's 25 worksheets along with a brief description of their functions:

a. *Flow Chart*—contains the diagram of the model structure shown in Figure H.1.

b. *Scenario Assumptions*—contains alternative data sets describing vehicle and fuel technologies, as well as a table in which the different data sets can be conveniently selected to construct fuel and vehicle technology scenarios. Alternative social values for reducing petroleum use and GHG mitigation may also be selected.

c. *Parameter Input*—contains most of the key assumptions of the model that a user will want to change in creating a new run.

d. *CO_2 Cost*—holds the alternative estimates of the social value of reducing carbon emissions from the U.S. government's interagency assessment of the social costs of carbon (Interagency Working Group, 2010).

e. *Hydrogen Stations*—contains the multinomial logit model used to estimate a smooth transition from a user-specified initial distribution of types of hydrogen stations to a user-specified long-run configuration as a function of the total volume of hydrogen production for LDVs.

f. *VISION*—used storing output from the Argonne National Laboratory's VISION model. The LAVE-Trans model can be forced to match the market shares of a VISION run. In that mode, it calculates the costs and benefits of achieving the particular VISION scenario.

g. *Vehicle Attributes*—contains the key vehicle attributes, by year, from 2010 to 2050. Most are derived from data contained in the Parameter Input worksheet.

h. *Risk Groups*—contains assumptions and calculations about innovators and majority adopters. At present these are the only two classes of consumers.

i. *Choice Parameters*—where the coefficients of the nested multinomial logit (NMNL) model for predicting choices among technologies are calculated.

j. *Vehicle Production*—where learning-by-doing, scale effects, and rates of exogenous technological progress are applied to the prices of technologies to estimate RPEs by year.

k. *Vehicle Choice*—the above factors come together to estimate market shares for each technology for new vehicles, as well as household's decisions to buy or not buy a new vehicle in a given year. Consumers' surplus is calculated here as well. Also calculated here are the cost components (i.e., cost of lack of fuel availability, cost of lack of diversity of choice, etc.) that also comprise the positive network externalities generated during the transition.

l. *Vehicle Sales*—the choices are applied to total vehicle sales (which will vary by time as the buy/no-buy decision changes each year) to produce estimates of sales by passenger cars and light trucks, by technology type and for innovators and majority. Also calculated in this worksheet are cumulative production, learning-by-doing, scale economies, and choice diversity.

Next come a series of large worksheets that depend on vehicle stock turnover.

m. *Vehicle Stock*—adds new vehicles to the existing fleet and scraps older vehicles by vintage. There are 10 tables (PC versus LT) × (five technologies).

n. *Vehicle Use*—multiplies kilometers per vehicle by vehicle age by the number of vehicles in the vehicle stock to estimate vehicle kilometers traveled (VKT) by vehicle type, technology type and 25 vintages. A rebound effect is built in to represent the tendency of vehicle use to increase when fuel cost per kilometer declines.

o. *Energy Use*—uses the vehicle efficiency estimates by vintage together with an on-road adjustment factor to estimate energy use by the same 250 categories for all years 2010 to 2050.

p. *PHEV Energy*—divides PHEV energy use into electricity and gasoline.

q. *GHG Emissions*—applies fuel specific well-to-wheel GHG factors to estimate emissions in CO_2 equivalents, again for all vehicle types, technology types, vintages, and years.

r. *Fuel Input*—contains information about the capital, operating, and delivery costs of alternative LDV energy sources and their lifecycle GHG emissions.

s. *Input USA*—where the projections of U.S. vehicle sales by vehicle type and technology type are stored. In addition to vehicle projections there are U.S. VKT projections, energy price projections, value of time projections (related to income per capita) and demographic projections (e.g., numbers of households).

t. *Input World* —where the assumptions about the production of alternative energy vehicles outside of the United States are input. These projections are exogenous and never changed by the model.

u. *Current Case*—contains summaries of costs, GHG emissions, energy use, vehicle stocks, vehicle sales, and VKT for the current case running in the model. The energy efficiency of the on-road vehicle stock is calculated in this worksheet, as well as average GHG emissions rates. The Current Case can be stored in the Base Case worksheet by clicking on a button that executes a macro that copies it to that location.

v. *Base Case*—should reflect the same scenario assumptions about technologies and energy costs as the Current Case. The two cases will be compared in the Costs-Benefits worksheet.

w. *Business as Usual Case*—may be stored in the BAU worksheet; should reflect the assumptions of the vehicle sales and vehicle travel projections to which the model has been calibrated, for example, a Reference Case projection of the EIA's AEO.

x. *Costs-Benefits*—Once a Current Case has been copied to the Base Case worksheet, changes to the model's inputs and parameter assumptions create a new Current Case. Differences between the Base Case and the Current Case are calculated in the Costs-Benefits worksheet. Here one will find the infrastructure, vehicle and fuel subsidy costs, changes in consumers' surplus, and societal benefits due to reductions in GHG emissions and petroleum use.

y. *Output*—contains a summary and comparison of the BAU Case, Base Case, and Current Cases, via a fixed set of tables and graphs.

H.2.3 Description of Model Components

In this section, the theory and equations of each key LAVE-Trans model component are presented and explained.

H.2.3.1 Vehicle Choice Model

Consumer demand is represented by a discrete choice, NMNL model, including a buy/no-buy choice. The buy/no-buy choice represents consumers' decisions to buy a new motor vehicle or to use their income for something else. In each time period, each household is assumed to make a buy versus no-buy decision. This allows for a more complete estimation of consumers' surplus effects, as well as allowing vehicle sales to increase or decrease in response to changes in policies or assumptions about technologies.

The vehicle choice model is a representative consumer model. Although it is desirable to segment the consumer market to reflect the heterogeneity of consumers' preferences, this comes at a high price in terms of the complexity of the model and its input data requirements. In the LAVE-Trans model, the market is split into only two segments: innovators/early-adopters versus the majority. More complex market segmentation could be added in a subsequent model development effort, if warranted.

The LAVE-Trans NMNL model allows a variety of factors, X_{ij}, including make and model diversity and fuel availability, as well as price, energy efficiency, and range to determine the utility, U_i, of each technology, i. Price is a special variable in the utility function, because its coefficient has units of utility per present value dollar. Thus, if the value of any attribute can be estimated in terms of dollars per unit of the attribute (e.g., present value dollars per MJ/km of fuel consumption), then its coefficient can be determined by multiplying the value per unit times the coefficient of price, β_k (where k is an index of the technology class, or nest, to which alternative i belongs). In this way, every coefficient in Equation H.2 is a function of the sensitivity of utility to price.

$$U_i = \sum_{j=1}^{n} \alpha_j X_{ij} + \beta_k P_i = \beta_k \left(\sum_{j=1}^{n} \frac{\alpha}{\beta_k} X_{ij} + P \right) \tag{H.2}$$

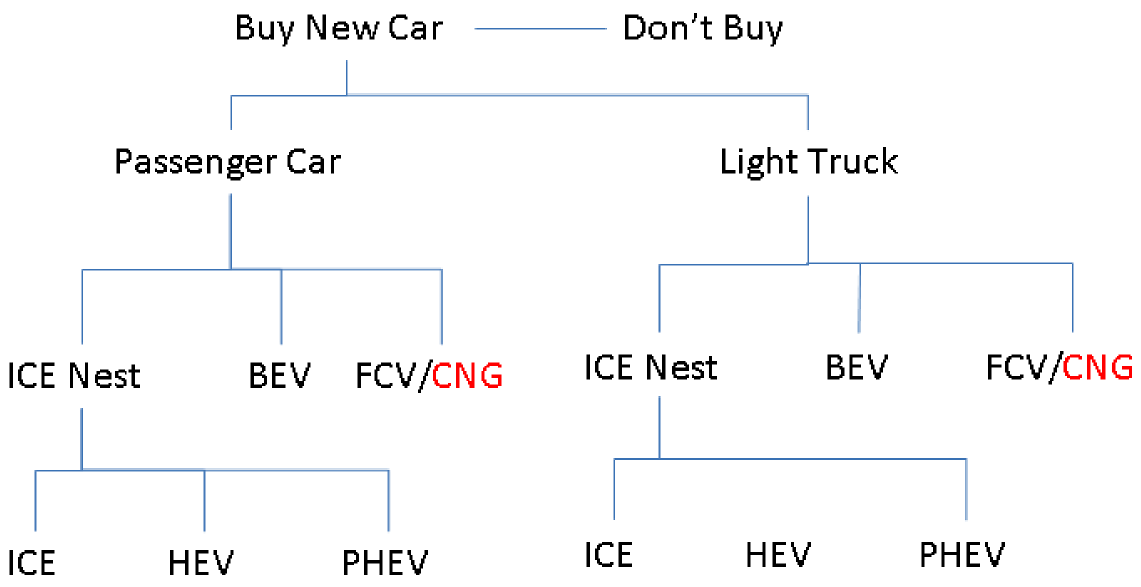


FIGURE H.2 Nesting structure of the LAVE-Trans model.

The NMNL model allows for some control over the patterns of substitution among vehicle technologies. In particular, vehicles within a given nest are closer substitutes for one another than they are for vehicles in a different nest.[5] The nesting structure used in the model is shown in Figure H.2. The first level of choice is to buy or not to buy a new LDV. The second is the choice between a passenger car and a light truck. The third level is the choice between an ICE, a BEV, and an FCV. The model allows the user to substitute a CNG vehicle for the FCV, but the number of technology choices has been limited to five for the sake of simplicity. Within the ICE nest is the choice between a conventional ICE, an HEV, and a PHEV. The order of nesting does not signify a temporal sequence of choices. Rather, it orders choices from least price sensitive (buy versus no-buy) to most price sensitive (ICE, HEV, or PHEV) and attempts to group choices within a nest that are closer substitutes than choices within some other nest.

The ability to translate attributes into dollar values is useful for measuring the network externalities that arise in the transformation of the energy basis for motor vehicles. For example, increasing fuel availability by adding public recharging stations or hydrogen fueling stations will reduce fuel availability costs. This improvement in fuel availability can be translated into an indirect network externality and be given a dollar value per vehicle using the relationships in Equation H.2. Likewise, if an innovator purchases a novel technology vehicle, this generates benefits for subsequent purchasers increasing scale and learning-by-doing, bringing down the price of vehicles, and by reducing the risk perceived by the majority market segment.

Market shares depend on each alternative's utility indexes, U_{ik}. At the lowest level nests, the probability of choosing alternative *i*, given that a choice will be made from nest *k*, $P_{i|k}$, is given by the logit equation in which *e* is the base of the Naperian logarithms, and *m* indexes other choices in nest *k*.

$$P_{i|k} = \frac{e^{U_{ik}}}{\sum_{m=1}^{M} e^{U_{mj}}} \tag{H.3}$$

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[5] More precisely, vehicles are more similar in their "unobserved attributes," meaning attributes that are not included in the model. For example, the sound of an electric-drive vehicle will be different from that of an ICEV, and this may influence consumers' choices.

The probability that a choice will be made from nest *k* depends on all the alternatives in nest *k*, as well as the utilities of all other nests at the same level. Let the measure of the utilities of all alternatives in nest *k* be represented by I_k, the "inclusive value" of nest *j*.

$$I_k = \frac{1}{\beta_k} \ln\left[\sum\nolimits_{i=1}^{N_I} e^{U_i}\right] \tag{H.4}$$

The probability of a choice being made from nest *j* is a logit function of the inclusive values of *j* and the other nests (indexed by *k*) at the same level as *j*.

$$P_j = \frac{e^{A_j + \beta I_j}}{\sum\nolimits_{k=1}^{N_k} e^{A_k + \beta I_k}} \tag{H.5}$$

In Equation H.5, β is the price coefficient for the choice among nests. The parameter A_j reflects aspects of nest *j* that are common to all members of the nest. In the LAVE-Trans model, the A_j parameters are generally set to zero, except at the level of choice between passenger car and light truck and buy versus no-buy. These coefficients are used to calibrate the choice model to a baseline sales forecast for passenger cars and light trucks. The procedure for calculating inclusive values can be used for any degree of nesting choices by simply passing inclusive values up to the next level.

The probability that technology *i* will be selected from nest *j* is the product of the probability of choosing nest *j* and the probability of choosing *i*, given that a choice will be made from nest *j*: $P_{ij} = P_{i|j}P_j$. This relationship is repeated as one moves from the lowest nests up to the buy/no-buy decision.

The NMNL model also allows direct calculation of the change in consumers' surplus due to changes in the prices and attributes of the choice alternatives. The change in consumers' surplus per household between the base case and an alternative scenario can be calculated at the top of the nesting structure from the utilities of the buy and no-buy choices. The superscript 0 indicates the Base Case, and the superscript 1 indicates the Scenario Case, and β^* is the price coefficient of the buy/no-buy choice.

$$\Delta CS = -\frac{1}{\beta^*}\left[\ln\left(e^{U^1_{buy}} + e^{U^1_{no-buy}}\right) - \ln\left(e^{U^0_{buy}} + e^{U^0_{no-buy}}\right)\right] \tag{H.6}$$

H.2.3.2 Calibration of Choice Model Parameters

The following nine variables determine the market shares of the alternative advanced technologies:

1. Retail price equivalent (RPE),
2. Energy cost per kilometer,
3. Range (kilometers between refuel/recharge events),
4. Maintenance cost (annual),
5. Fuel availability,
6. Range limitation for BEVs,
7. Public recharging availability,
8. Risk aversion (innovator versus majority), and
9. Diversity of make and model options available.

NMNL models can be calibrated to the best available evidence on the sensitivity of consumers' choices to vehicle prices and the value consumers attach to vehicles' attributes, including range, fuel economy, performance, fuel availability, and diversity of choice. The procedure requires estimating the present dollar value per unit of the attribute, which can then be multiplied by the price coefficient to derive a coefficient that translates one unit of the attribute into a utility index. Each of the attributes and the method for estimating its NMNL model coefficient is considered below.

H.2.3.2.1 Diversity of Choice Among Makes and Models

Make and model diversity is represented in the vehicle choice model as the log of the ratio of the actual number of makes and models available, *n*, to the "full diversity" number, *N*, represented by the number of makes and models of the conventional technology available in the base year, ln(*n*/*N*) (for a derivation, see Greene [2001], pp. 21-22). This variable is then multiplied by a coefficient (e.g., a default value of 0.67 is used in most cases) that depends on the cumulative sales distribution across makes and models. The number of makes and models available in any given year can be determined by dividing total sales by the production volume at which full scale economies are achieved.[6]

H.2.3.2.2 Consumers' Aversion to the Risk of New Technology

Consumers' risk aversion to new technologies (the early adopter, early majority, and late majority phenomenon) is represented in a manner analogous to learning by doing. Innovators have a preference for novel technologies (a utility premium) that decreases with cumulative sales. The majority of the market may have an aversion for novel technologies (a negative utility) that decreases with cumulative sales. These are represented by exponential "cost" functions that enter into the consumers' utility functions. Each group is assigned a monthly quantity to either avoid (+ cost) or gain (− cost) the opportunity to purchase a vehicle with novel technology. The monthly payments are discounted to present value assuming a certain length of loan or lease (e.g., 48 months) and annual real interest rate (e.g., 7 percent). A slope coefficient for the exponential function is estimated by specifying the cumulative sales point at which the risk or novelty value of the new technology will be reduced by half. The slope coefficient, b_i, is the logarithm of 0.5 divided by the specified cumulative sales. Given the estimated present value, V_i, for group *i* and slope coefficient, b_i, the risk to majority buyers and the novelty value to innovators, v_{ij}, is a function of cumulative sales of technology *j*, Q_j.

$$v_{ij} = V_i e^{b_i Q_j} \tag{H.7}$$

In the current version of the model, the market is divided into only two groups: innovators and the rest of the market represented by the majority. The percent of the market in each group can be specified.

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[6] This implies that the diversity of choice for the conventional technology is total sales divided by the same full scale production volume. For example, if conventional LDV sales are 15 million in the base year and the production level for full scale economies is 100,000, then the diversity measure would be *N* = 150 for conventional vehicles.

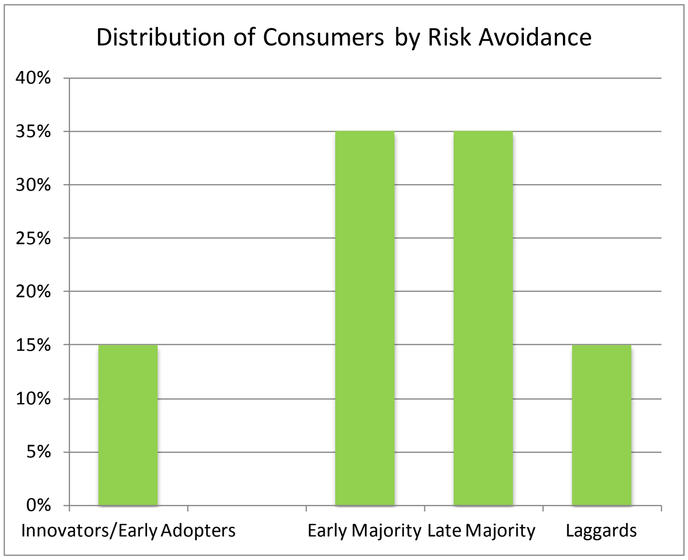

FIGURE H.3 Default distribution of consumers by aversion to risk of new products.

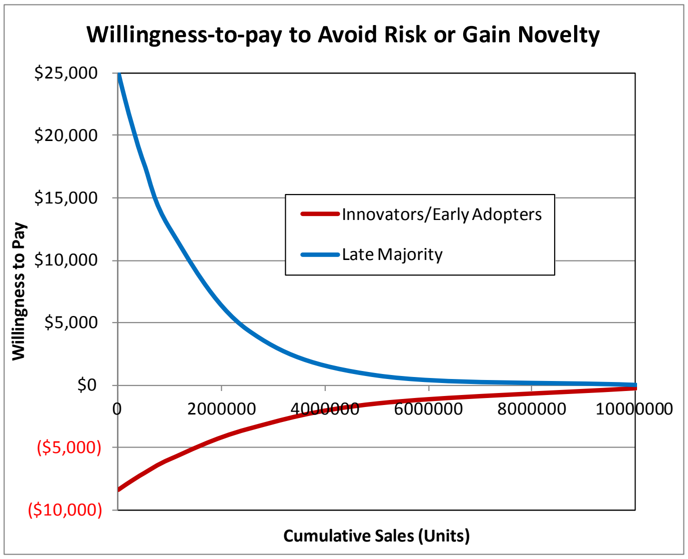

FIGURE H.4 Default willingness-to-pay functions for innovators/early adopters and majority.

H.2.3.2.3 Value of Energy Efficiency

The value of energy efficiency is represented by the present value of future fuel savings. The way consumers value future fuel savings is a largely unresolved issue, with the econometric evidence split roughly 50/50 between undervaluing versus accurately valuing or overvaluing (Greene, 2010). If consumers consider paying more up front for future fuel savings a risky bet, behavioral economics implies that consumers will undervalue future fuel savings by one-half or more (Greene, 2011). The LAVE-Trans model allows for different specifications of consumers' valuation of future fuel costs within the context of discounting to present value. The following variables determine the present value of future fuel costs:

E = a vehicle's energy efficiency in MJ/km,
P = the price of energy per MJ,

M_0 = the vehicle's annual kilometers when new,
L = the vehicle's lifetime in years,
r = the consumers' discount rate, and
δ = the rate of decline in vehicle use with vehicle age.

The present value of fuel costs is the integral over the vehicle's lifetime of the instantaneous fuel costs.

$$PV = \int_{t=0}^{L} PEM_0 e^{-rt} e^{-\delta t} dt = P\left[\frac{1}{(r+\delta)}\left(1-e^{-(r+\delta)L}\right)M_0\right] \tag{H.8}$$

In Equation H.8 it is assumed that the price of fuel over the life of the vehicle is constant. While this is certainly incorrect, it is consistent with rational expectations given fuel prices that follow a random walk (Hamilton, 2009). If the discount rate is set to zero and L is set to 3, for example, this formula becomes a 3-year payback formula. The term in square brackets is discounted vehicle travel, which is useful in estimating the value of other vehicle attributes, such as range.

The variable representing energy efficiency is energy cost per kilometer. The coefficient of vehicle energy cost per kilometer ($/MJ × MJ/km) is discounted lifetime kilometers (the term in square brackets in Equation H.8 multiplied by the price coefficient.

H.2.3.2.4 Value of Maintenance Costs

Maintenance costs are assumed to be incurred annually over the life of a vehicle. The vehicle attribute is defined as annual maintenance costs in dollars. Thus, the coefficient is discounted years of vehicle life multiplied by the price coefficient. Discounted years are equal to the term in square brackets of Equation H.9. The time horizon over which maintenance costs are discounted is allowed to be different from that for fuel costs to allow flexibility in representing consumer behavior.

$$DY = \int_{t=0}^{L} e^{-rt} dt = \left[\frac{1}{r}\left(1-e^{-(r)L}\right)\right] \tag{H.9}$$

H.2.3.2.5 Value of Range

The value (or cost) of range is calculated as the discounted present value of time spent refueling over the life of the vehicle. The range variable is defined as the time required per refueling (in hours), t_r, multiplied by the value of time (in $/hr), v, divided by kilometers per tank of fuel or kilometers per charge. Thus, it is the inverse of range that determines the value of range. Kilometers per tank is calculated by multiplying usable energy storage in gallons of gasoline equivalent, q, times the number of MJ per gallon, c, and dividing by the vehicle's energy efficiency in MJ/km, E. The denominator of the term in the righthand-most brackets of Equation H.10, cq/E, is what is usually defined as vehicle range: kilometers per tank or per charge. The cost of increased range falls inversely with range. On-board energy storage capacity and vehicle energy efficiency may change over time, as may the value of time and the time required to refuel. It is assumed that neither a fuel tank nor a battery will be completely exhausted before it is replenished. Energy storage capacities should, therefore, be specified in terms of usable energy storage rather than total energy storage. In Equation H.10, the term in round brackets is the coefficient of range, while the term in {} brackets is the range variable. The coefficient of range is discounted lifetime kilometers multiplied by the price coefficient. The range variable is the value of time spent refueling per kilometer of vehicle travel.

$$\left(\beta\left[-\left(\frac{1}{r+\delta}\right)\left(1-e^{(r+\delta)L}\right)\right]M_0\right)\left\{\frac{t_r v}{cq/E}\right\} \qquad \text{(H.10)}$$

Equation H.10 does not accurately represent the recharging cost for PHEVs. For PHEVs, the time required to fully recharge a battery is likely to be hours, but the driver will not stand by idly while the vehicle charges. The EV's problem is a combination of limited range and long recharge time. In the LAVE-Trans model, Equation H.10 is used only to account for the time require to plug and unplug the vehicle. It assumed that during recharge the driver is able to use his or her time productively in other pursuits and that, therefore, the cost is zero. On the other hand, the combination of long recharge time and short range will make the plug-in vehicle unable to accommodate motorists' desired travel on those days when the desired travel exceed the vehicle's range. We use a different method, described in Section H.2.3.2.8, to account for those costs.

H.2.3.2.6 Value of Fuel Availability

The value of fuel availability is a key component of transition costs; it is the fuel half of the "chicken or egg" problem for alternative fuels. Despite some very good recent research (e.g., Nicholas et al., 2004; Nicholas and Ogden, 2007; Ogden and Nicholas, 2010; Melaina and Bremson, 2008), quantifying the value of fuel availability remains a challenge. The estimate used here begins with a measure of the extra time required to access fuel in a metropolitan area as a function of the ratio of the number of stations offering the alternative fuel to a reference number of gasoline stations. The fuel availability variable in the Vehicle Attributes spreadsheet is that ratio. The method is based on simulation modeling by Nicholas et al. (2004) and was used in the Department of Energy's modeling of market transitions to hydrogen (Greene et al., 2008).

The coefficient of the fuel availability variable is the coefficient of vehicle price times discounted lifetime kilometers (the term in square brackets in Equation H.8) times a multiplier that represents the ratio of the total cost of fuel availability to the cost of access time within one's own metropolitan area. This multiplier, which is given a default value of 3, represents the extra value of regional and national fuel availability, as well as the added fear of risk of running out of fuel. This is generally consistent with the results of Melaina's (2009) stated preference analysis of consumers' preferences for refueling availability, which found very roughly comparable values for availability in (1) one's metropolitan area, (2) regionally, and (3) nationally.

The fuel availability term in the choice model combines the effects of range, R, and fuel availability, $f_j = n_j/N_0$, where n_j is the number of stations offering fuel for technology j and N_0 is the reference number of stations (i.e., the number of gasoline refueling stations in the base year). As range increases, fuel availability decreases in importance because the number of refueling events decreases. In Equation H.11, B_f is the coefficient of the fuel availability variable (discounted lifetime kilometers multiplied by the price coefficient), w is the value of time in \$/hour, C is a coefficient from the Nicholas et al. (2004) model relating the number of stations to access time, and a is the second coefficient of that model.

$$B_f w\left(\frac{1}{R}\right)\left[CN_0^{\alpha}\left(f_j^{\alpha}-1\right)\right]=\left\{\beta\left[-\frac{1}{r+\delta}\left(1-e^{(r+\delta)L}\right)\right]M_0\right\}\left\{w\left(\frac{1}{R}\right)\left[CN_0^{\alpha}\left(f_j^{\alpha}-1\right)\right]\right\} \qquad \text{(H.11)}$$

The term in square brackets in Equation H.11 is the extra access time required per refueling event, which is converted into a dollar value by the value of time, w. The $1/R$ term adjusts the coefficient B_f for changes in vehicle range over time due to improved energy efficiency or energy storage.

Representing fuel availability as a ratio to a reference number of outlets is an approximation of a much more complex process. In the earliest stages of infrastructure evolution, stations are likely to be placed in clusters near concentrations of FCV owners; clustering will be a self-reinforcing process. Ogden and Nicholas (2010) estimated that in the Los Angeles, California, area, as few as 42 stations could provide one station that is within 2.6 minutes of home for clustered FCV owners. If stations were distributed by population density instead, it would require 4 to 15 times as many stations, 1.5 to 3 percent of the number of gasoline stations in the Los Angeles basin.

H.2.3.2.7 Value of Public Recharging

The value of the availability of public recharging to BEVs is a function of the present value of full availability of public recharging versus none, based on an analysis by Lin and Greene (2011a). That study derived a value of public recharging as a function of the number of days in a year an EV would not be able to satisfy typical kilometers traveled and the cost of renting a vehicle with unlimited range for those days. Let V be the present value of unlimited public recharging, f the availability of public recharging relative to the availability of gasoline stations, and β be the coefficient of vehicle price, and b be a slope coefficient. The value of public recharging is given by Equation H.12. It increases from 0 to approach V as f increases from 0 to 1.0.

$$\beta V\left(1-e^{bf}\right) \tag{H.12}$$

This method is very approximate and should be improved. In particular, the value of public recharging should also depend on vehicle range.

The value of public recharging to PHEVs is estimated by an equation identical in form to Equation H.12, also based on the analysis by Lin and Greene (2011a). The price coefficient, β, value, V, and slope b are specific to PHEVs, however.

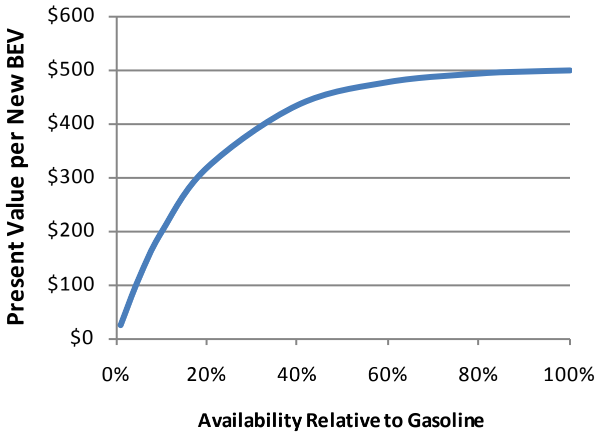

FIGURE H.5 Estimated present value of public recharging for a new battery electric vehicle.

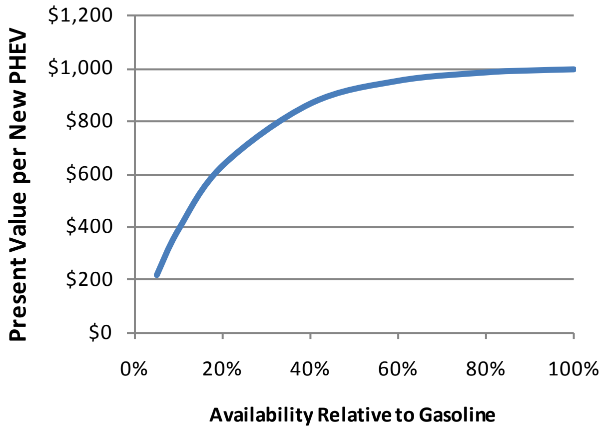

FIGURE H.6 Estimated present value of public recharging for a new plug-in hybrid electric vehicle.

H.2.3.2.8 Value of Range Anxiety

Range anxiety typically describes the fear of being stranded that the owner of a vehicle with limited range, long recharging time, and limited availability of public recharging may experience. The perceived cost of this form of range anxiety is likely to vary greatly from individual to individual and over time, as well, as drivers learn about their vehicles. In the LAVE-Trans model range anxiety is defined differently as the loss of utility due to a vehicle's inability to be used for more than a certain number of miles per day. Range anxiety declines exponentially at a rate *b* from a theoretical maximum value at zero range, *X*, to asymptotically approach zero as range *R* goes to infinity. Once again, *β* is the coefficient of price. The values shown in Figure H.7 were taken from Lin and Greene (2011b), who calculated the number of days a vehicle with range *R* would be unable to accomplish the daily driving pattern of typical U.S. drivers. Lin and Greene (2011b) suggest a daily penalty of $15 to $30, which is typically less than the cost of renting a vehicle to accomplish the usual driving, because motorists have other options, especially if the household owns more than one vehicle.

$$\beta X e^{bR} \tag{H.13}$$

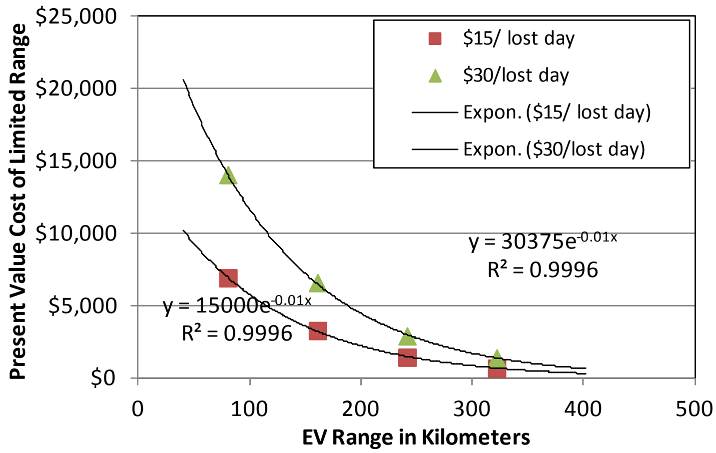

FIGURE H.7 Present value cost of limited range (range anxiety) for a new BEV.

H.2.3.3 Vehicle Sales and Vehicle Production

Sales of alternative vehicles generate positive feedback for these new technologies by inducing learning by doing, scale economies, greater diversity of choice in the number of makes and models, and by reducing majority consumers' aversion to risk. Sales by vehicle type (passenger car versus light truck) and by technology type are estimated by multiplying total sales by the shares predicted by the NMNL vehicle choice model.

Base Case sales are calibrated to exactly match exogenous total LDV sales by means of year-specific constants for the buy/no-buy choice. Similarly, the shares of passenger cars and light trucks are individually matched to the exogenous Base Case projection by calibrating a constant term for the NMNL car versus truck choice for each year. This insures that for the Base Case only, total sales as well as car and light truck sales exactly match the exogenous projection. In policy scenarios, changes in vehicle technology and new policies (e.g., vehicle or fuel taxes or subsidies) can not only change the market shares of vehicle technologies but the split between passenger cars and light trucks and total sales, as well. The calibration constants are calculated iteratively by first estimating an initial value, substituting that value into the NMNL choice model, and then recalculating a new value. Iteration is necessary because the calibration constants affect shares, which in turn determine sales, and sales affect the utility indexes for vehicles via fuel prices, learning by doing, scale economies, make and model diversity, and fuel availability. Let I_C and S_C be the inclusive value and Base Case market share, respectively, for passenger cars, and I_T and S_T are the corresponding values for light trucks. The initial estimate of the light truck constant term is the following (in which the superscript 1 indicates the first iteration).

$$A_T^1 = I_C^1 - I_T^1 - \ln\left(\frac{S_T}{1-S_T}\right) \tag{H.14}$$

When the calibration constant is substituted in the vehicle choice equation, it results in different market shares and, therefore, sales for cars and light trucks, which affects their prices and other attributes via the feedback mechanisms of learning, scale economies, etc. This in turn affects the inclusive values, resulting in a different estimate for the constant term via Equation H.14. The process is repeated until the constant terms are determined to at least four-digit accuracy. A similar process is used to simultaneously estimate the year-specific constant terms for the buy/no-buy choice. Typically, convergence is achieved over the 40-year forecast horizon in about 10 iterations.

Via several feedback mechanisms, vehicle sales affect future vehicle prices, numbers of makes and models from which to choose, and fuel availability. The key mechanisms affecting the prices of new technologies during the early stages of a transition are learning by doing and scale economies. Learning by doing is represented by declining costs as a function of cumulative production, Q, relative to an initial reference level, Q_R. The rate of learning, or progress ratio, α, represents the impact of a doubling of cumulative output on cost. Let $P(Q_0)$ represent the RPE at cumulative production Q_0, then the RPE at cumulative production level $Q > Q_0$ is given by Equation H.15.

$$P(Q) = P(Q_0)\left[\frac{Q}{Q_0}\right]^{\alpha} \tag{H.15}$$

This formulation has a significant drawback, namely that costs can decline to zero as cumulative output approaches infinity. The LAVE-Trans model limits the reduction in cost so that costs converge to the long-run RPE estimates provided by model users.

Scale economies are represented by a scale elasticity, c, which is the exponent of the ratio of production volume in a given period, q, to the ideal production volume, q^*, at which full-scale economies are realized. RPE is equal to the ideal RPE, P^*, times the ratio q/q^* raised to the c. Values of the scale elasticity, c, are often in the vicinity of −0.25, implying that a doubling of volume reduces costs by about 15 percent. Once $q >= q^*$, q is set = q^* so that the scale elasticity factor will never be smaller than 1.0.

$$P(q) = P^* \left(\frac{q}{q^*} \right)^c \tag{H.16}$$

Technological progress is determined by user-specified prices, energy efficiencies, and other attributes, which are key exogenous inputs to the model. The technologically achievable price at time t, P_t, is defined as the RPE that could be achieved at full-scale and fully learned production. The user must specify the technologically achievable prices, energy efficiencies, and other vehicle attributes for 2010, 2015, 2020, 2030, 2040, and 2050. Technologically achievable prices and attributes for intervening years are estimated by linear interpolation. Attributes are assumed to be achieved regardless of current or cumulative sales. Prices must be driven down by learning and scale economies.

Using the above framework, the RPE of an advanced technology vehicle at any given time is the product of the technologically achievable price, P_t, times the technological progress, learning by doing, and scale economy functions.

$$P(Q,q,t) = P_t \times Max \left\{ P_t \left(\frac{Q}{Q_0} \right)^a \left(\frac{q}{q^*} \right)^c , P_t \right\} \tag{H.17}$$

H.2.3.4 Vehicle Stock

Vehicle stock, S_{cimt}, is the number of vehicles of class c (passenger car, light truck) and technology type i, manufactured in model year m, in operation in calendar year t. The default survival functions for cars and light trucks are taken from NHTSA (2006). Alternatively, a three-parameter scrappage/survival function can be used to retire a fraction of the vehicle stock each year as vehicles age. Let $R_i(a)$ be the scrappage rate function for vehicles of technology type i and age $a = t - m$, and A_{i0}, A_{i1}, and A_{i2} be parameters of the scrappage function. The scrappage rate is the fraction of vehicles of age $a - 1$ in year $t - 1$ that are retired (scrapped) in year t. The fraction of vehicles surviving to age a is $1 - R_i(a)$.

$$R_i(a) = \frac{1}{A_{i0} + e^{A_{i1} + A_{i2} a}} \tag{H.18}$$

The number of a-year-old ($a = t - m$) vehicles surviving from year t to year $t + 1$ is given by Equation H.19.

$$S_{cimt+1} = S_{cimt} \left(1 - R_i(a) \right) \tag{H.19}$$

Vehicle stock accounts are kept for 25 ages (0-24); vehicles older than 24 years are combined into a single >25 category and scrapped at a constant rate equal to $1/A_{i0}$.

H.2.3.5 Vehicle Use and Energy Use

Vehicle use, $V_i(a)$, is assumed to be primarily a function of vehicle technology and vehicle age, but it also varies with energy efficiency to account for the rebound effect and varies with growth in the

TABLE H.4 Parameters for National Highway Traffice Safety Administration Cubic Equation for Vehicle Use as a Function of Age

	C_3	C_2	C_1	C_0
Car	0.36721	−13.2195	−232.85	14476.4
Truck	0.68064	−22.8448	−238.55	16345.3

vehicle stock. Vehicle use as a function of age for passenger cars and light trucks is based on NHTSA (2006), which fitted cubic polynomials to annual mileage at 1-year age intervals. Annual miles for vehicle type *i* (passenger car, light truck) is given by Equation H.20.

$$V_i(a) = c_{0i} + c_{1i}a + c_{2i}a^2 + c_{3i}a^3 \tag{H.20}$$

The parameter values derived by NHTSA are shown in Table H.4. Vehicle miles are converted to kilometers by multiplying by 1.609. The resulting typical curves for passenger cars and light trucks are shown in Figure H.8. The same parameters may be used for every vehicle technology, or the user may specify different annual usage rates for different vehicle technologies. However, this should be done with caution. In the current version of the model, changing usage rates could profoundly affect total vehicle travel in scenarios in which low-usage vehicles become predominant. If a lower than average usage rate is specified for BEVs, a fraction of the reduction in travel will be shifted to other vehicle technologies. When a BEV’s range and recharging limitations make it unable to perform a consumer’s typical, desired daily travel, the consumer may (1) forego the travel or take a shorter trip, (2) shift the travel to another vehicle already owned, or (3) purchase or rent an additional vehicle. The model user can specify percentages for each option. The percentage allocated to option 1 will result in a decrease in total travel.

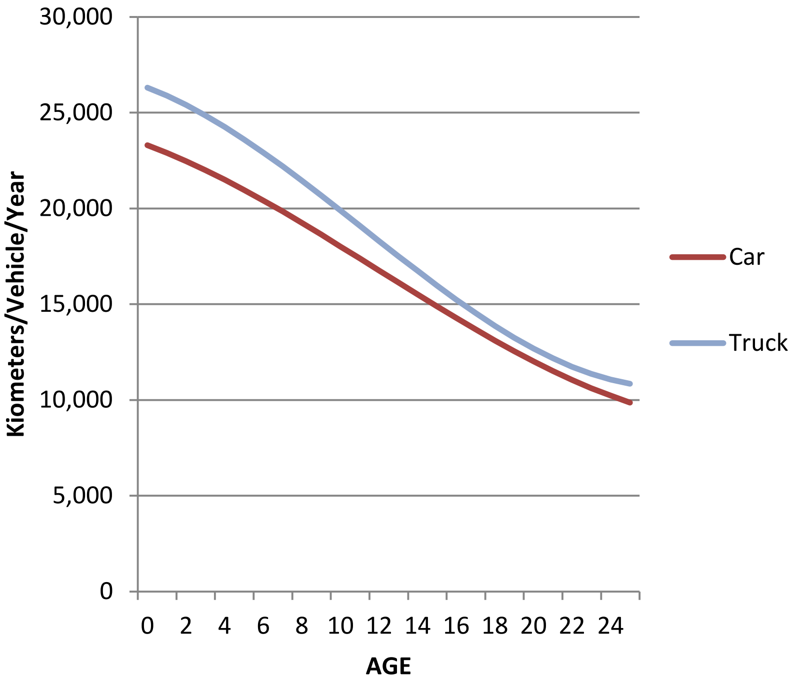

FIGURE H.8 Annual vehicle kilometers traveled by age of vehicle.

The percentages specified for options 2 and 3 will be allocated to other vehicle types. At present, the model does not allow vehicle sales to increase to accommodate option 3. For example, suppose a model user specified that 10 percent of the vehicle miles that could not be performed by a BEV would be foregone, 60 percent would be shifted to other vehicles, and 30 percent would be accommodated by the purchase of additional vehicles. If EVs comprised 10 percent of vehicles in use and were used on average 30 percent less than other vehicle types, there would be a 1.2 percent reduction in total VMT, and 1.8 percent of the travel would be shifted to the remaining 90 percent of vehicles, increasing their rates of use by 2 percent.

H.2.3.5.1 Adjustment for Changes in the Size of the Vehicle Stock

Because the vehicle choice model includes the option to buy or not to buy a new vehicle that depends on the attractiveness of new vehicles relative to other consumer goods, total LDV sales and stock size may change from one scenario to another. If annual kilometers traveled per vehicle (by age) were constant, then vehicle travel would increase approximately in proportion to the size of the vehicle stock. In fact, because the United States now has more motor vehicles than licensed drivers, vehicle travel is relatively insensitive to increases in the number of vehicles available for use. For example, Greene (2012) found that a 10 percent increase in number of LDVs in the United States would lead to only a 2 percent increase in total VKT in the long run.[7] Let the elasticity of total VKT with respect to the size of the vehicle stock be η. The effect of a change in the size of the vehicle stock in year t in scenario s, S_{ti}, compared to the stock in year t in the base case, S_{tB}, on annual kilometers by a vehicle of age a in year t, V_{ats}, is shown in Equation H.21.

$$V_{ats} = V_{ats}\left(\frac{S_{ts}}{S_{tB}}\right)^{\eta-1} \tag{H.21}$$

Thus, if the vehicle stock in a given scenario increases by, say 10 percent relative to the Base Case, annual kilometers per vehicle will decrease by 7.34 percent, resulting in an increase of total vehicle kilometers by a factor of (1.1) × (0.9266) = 1.019, or about 2 percent.

H.2.3.5.2 Adjustment of VKT for Changes in Fuel Cost per Kilometer

Adjusting vehicle travel for changes in the cost of energy per mile, also known as the “rebound effect,” is accomplished in two steps. In the first step, VKT per vehicle by year and vintage is adjusted relative to the base year of 2010. Let p_{it} be the price of energy for a vehicle of technology type i in year t, and E_{cimt} be the rate of energy consumption per kilometer for a vehicle of class c, technology i, model year m, in year t. Let γ be the rebound elasticity, the percent change in vehicle travel for a percent change in energy cost per kilometer. The first adjustment factor, k_1, is the energy cost per mile in year t relative to the energy cost per mile in the base year, raised to the rebound elasticity.

$$k_{1cimt} = \left(\frac{p_{it}E_{cimt}}{p_{i0}E_{cim0}}\right)^{\gamma} \tag{H.22}$$

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[7] This result pertains to models in which the sensitivity to fuel cost per mile was allowed to vary over time as a function of per capita income.

The elasticity of vehicle use with respect to fuel cost per kilometer of travel determines the percent change in travel per vehicle for a 1 percent change in fuel cost per kilometer. The default value, which may be changed by the model user, is −0.1, implying a 1 percent increase in travel for a 10 percent reduction in fuel cost per kilometer.

The second adjustment factor, k_{2t}, is the ratio of total projected light-duty VKT from the exogenous AEO forecast, $V_{AEO,t}$, relative to the model's initial estimate of VKT for the BAU Case, V^*_{BAU}. Multiplying the model's BAU VKT estimate by this factor insures that total VKT in the BAU Case will match the AEO projection in each forecast year.

$$k_{2t} = \frac{V_{AEO,t}}{V^*_{BAU,t}} \tag{H.23}$$

This parameter ensures only that travel in the BAU Case matches the AEO projection. When assumptions about vehicle energy efficiency or cost or other variables are changed in a Base Case or Current Case, VKT will, in general, differ from the AEO projection. In particular, if vehicle efficiency improves and purchase prices decline, vehicle travel will increase due to the rebound effect and the increased number of vehicles on the road.

Energy use for all vehicles, Z_{cimt}, is the product of vehicle stock, S_{cimt}, vehicle use, V_{ia}, and vehicle fuel consumption, E_{cim}, divided by 1,000,000 so that the units are terajoules per year.

$$Z_{cimt} = S_{cimt} V_{ia} E_{cimt} / 1000000 \tag{H.24}$$

H.2.3.5.3 PHEV Energy Use

For PHEVs, energy use must be divided between electricity and gasoline. This is done by multiplying total energy use assuming the vehicle is operated entirely in charge-sustaining mode times the share of kilometers traveled in charge depleting mode, s_d, times the relative energy consumption in charge-depleting mode compared to charge-sustaining mode, r_d. The relative energy use is calculated as the ratio of the energy efficiency in charge-depleting mode divided by energy efficiency in charge-sustaining mode.

$$Z_{cimtd} = Z_{cimt} s_{dt} r_{dt} \tag{H.25}$$

Gasoline energy use is then calculated as the product of total energy use assuming 100 percent charge depleting operation times 1 minus the share of kilometers in charge-depleting mode.

$$Z_{cimts} = Z_{cimt} \left(1 - s_{dt}\right) \tag{H.26}$$

H.2.3.6 GHG Emissions

GHG emissions are calculated by multiplying time-dependent emissions coefficients, g_{it}, times the quantity of energy used, Z_{cimt}. For PHEVs, two calculations are made, one for electricity consumption and another for gasoline consumption. Different emissions scenarios can be constructed by selecting alternative emissions coefficients for gasoline, electricity, hydrogen, and natural gas.

The GHG emissions of gasoline are computed as a weighted sum of its blend components' GHG emissions rates. Let s_i be the share of fuel type i (i = conventional gasoline, corn-based ethanol, cellulosic ethanol, drop-in pyrolysis biofuel, coal-to-liquid gasoline, gas-to-liquid gasoline), and let g_i be its estimated well-to-wheel emissions rate in kilograms of CO_2 per gasoline gallon equivalent energy. The GHG emissions rate of gasoline, g, is given by the following:

$$g = \sum_{i=1}^{6} s_i g_i \tag{H.27}$$

One of two scenarios can be selected for GHG emissions from electricity use. For the United States the GHG scenarios are based on the Reference Case and the Low Carbon Case of the GHG Price Case projections for the U.S. electricity grid of the EIA AEO 2011 extrapolated from 2035 to 2050.

Three alternative scenarios can be used for GHG emissions from hydrogen use. In all cases, emissions are assumed to be 11.44 kg CO_2 per gge until hydrogen production reaches 6,000 metric tons per day (tpd; approximately enough to fuel 6 million vehicles). In a low-cost hydrogen case, no sequestration is assumed, and based on a mix of 25 percent distributed natural gas reforming, 25 percent coal gasification without CCS, 25 percent central natural gas reforming without CCS, and 25 percent biomass gasification without CCS, an emission factor of 12.2 kg/gge is used. A carbon sequestration case adds CCS to central coal and natural gas production but not distributed natural gas or central biomass, resulting in an emissions factor of 5.1 kg/gge. A low-CO_2 case assumes only 10 percent distributed natural gas reforming, 40 percent central natural gas reforming with CCS, 30 percent biomass gasification without CCS, and 20 percent emission-free electricity (e.g., wind) for electrolysis, resulting in an emissions factor of 2.6 kg/gge.

H.2.4 Energy Infrastructure, Prices, and GHG Emission Rates

The costs of fuel supply infrastructure are estimated for electricity, hydrogen, and CNG. A distinction is also made between infrastructure necessary to support sales of vehicles and infrastructure added by public policy to increase fuel availability beyond the minimum necessary to support the stock of vehicles on the road. A model user may specify a fixed amount of infrastructure (or fuel supply) to be added as vehicles are sold and also the quantities and types of infrastructure deployed by subsidies or mandates.

H.2.4.1 Hydrogen

The hydrogen production and dispensing submodel estimates the number of hydrogen stations by type of station, the current price of hydrogen, and the average GHG emissions per kilogram of hydrogen used. For each hydrogen vehicle sold, it is assumed that enough fuel to operate the vehicle will be supplied and that only enough stations to provide that fuel will be constructed. The model user may require additional stations to increase fuel availability, but any additional stations will be fully subsidized (by government or industry).

The flow of the hydrogen production and delivery model is diagrammed in Figure H.9. The input data that define a hydrogen scenario consist of (1) long-run, high-volume hydrogen production costs,[8] (2) GHG emissions per gallon of gasoline equivalent energy, and (3) target production process shares, all by production process and for the years 2010, 2020, 2035, and 2050 (e.g., Table H.5).

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[8] A future version of the model will build up these estimates from data on capital, operating and feedstock requirements and costs, as well as required returns on investment.

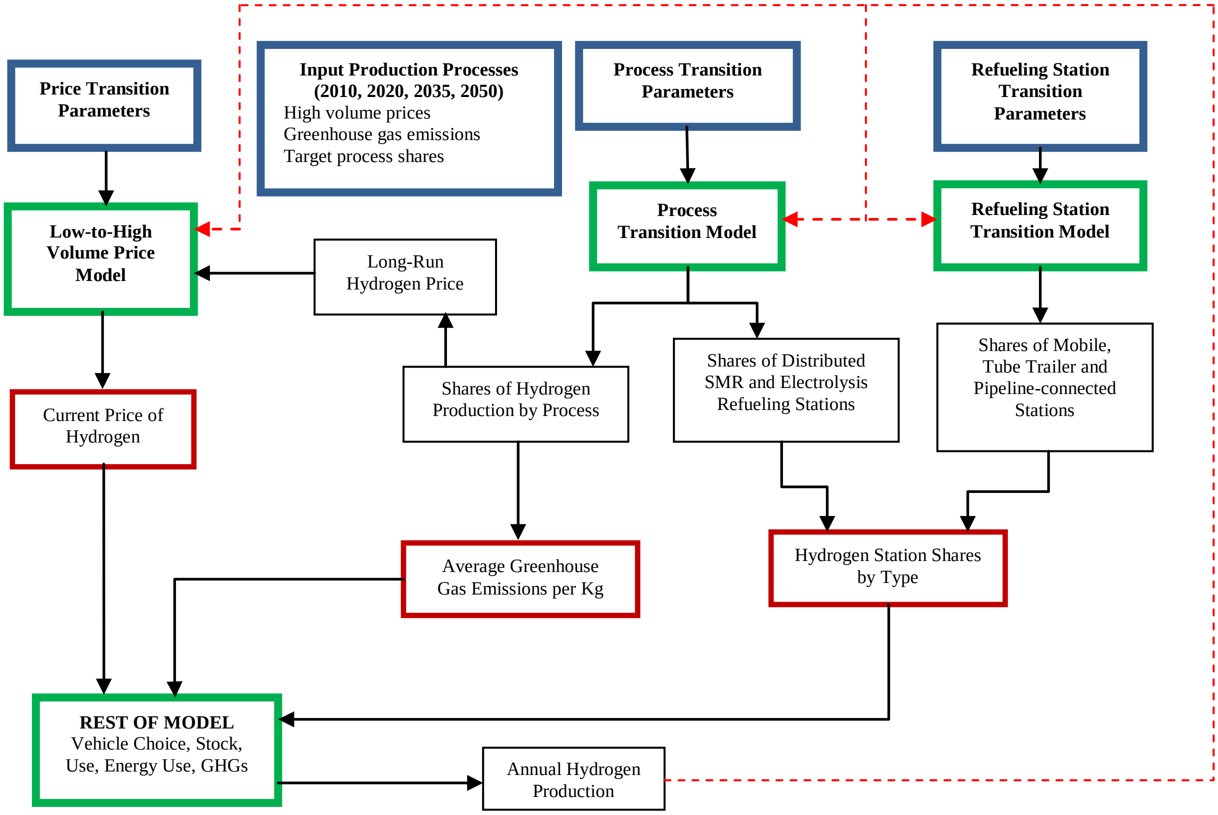

FIGURE H.9 Flow chart of hydrogen production and delivery model.

In the LAVE-Trans model hydrogen may be produced by the following eight processes:

1. Distributed natural gas reforming,
2. Distributed grid electrolysis,
3. Central coal gasification without CCS,
4. Central coal gasification with CCS,
5. Central natural gas reforming without CCS,
6. Central natural gas reforming with CCS,
7. Central biomass gasification without CCS, and
8. Central biomass gasification with CCS.

However, the processes chosen to produce hydrogen and the cost of hydrogen are not independent of the scale of hydrogen production. Early on, when production volumes are low, distributed production and distribution from central plants by mobile refueling units or tube trailers are likely to predominate. Later, as hydrogen production reaches thousands of tons per day, production is likely to favor more efficient central plants connected via pipeline to refueling outlets.

The process transition model makes a smooth transition from the initial production processes specified to the future year production processes specified by the user, as a function of the volume of production. The calculations of process shares, average costs, and average GHG emissions are carried out in three steps. First, production process shares for the intervening years are linearly interpolated between the specified years. Second, the process transition parameters are used to calibrate a logistic function of

TABLE H.5 Illustrative Assumptions for Production Shares by Process, GHG Emissions Rates and Long-Run Costs of Hydrogen

	Production Shares				Greenhouse Gas Emissions (kg/gge)				Delivered Costs of Hydrogen ($/kg)			
Process	2010	2020	2035	2050	2010	2020	2035	2050	2010	2020	2035	2050
Distributed NG reforming	50%	50%	25%	25%	11.44	11.44	11.44	11.44	$3.49	$3.60	$3.90	$4.20
Distributed grid electrolysis	0%	0%	0%	0%	35.44	35.44	35.44	35.44	$5.76	$5.38	$5.54	$5.69
Central coal gasification without CCS	0%	0%	0%	0%	25.81	25.81	25.81	25.81	$3.81	$3.82	$3.84	$3.85
Central coal gasification with CCS	0%	0%	25%	25%	5.24	5.24	5.24	5.24	$4.46	$4.46	$4.48	$4.49
Central NG reforming without CCS	50%	50%	0%	0%	11.46	11.46	11.46	11.46	$3.28	$3.36	$3.69	$4.01
Central NG reforming with CCS	0%	0%	25%	25%	3.64	3.64	3.64	3.64	$3.55	$3.63	$3.96	$4.28
Central biomass gasification without CCS	0%	0%	25%	25%	0.20	0.20	0.20	0.20	$4.09	$4.09	$4.09	$4.09
Central biomass gasification with CCS	0%	0%	0%	0%	−21.73	−21.73	−21.73	−21.73	$4.74	$4.73	$4.73	$4.73

the annual volume of hydrogen production. This function is bounded by zero and 1, and predicts the degree to which the transition from initial production methods to the user-specified shares for future years has been accomplished. The process transition parameters consist of two points on the logistic curve, e.g., fractions of the transition, f_1 and f_2, accomplished at corresponding production volumes v_1 and v_2. These define a two-parameter logistic function of the volume of production.

$$f(v) = \frac{1}{1+e^{A+Bv}} \tag{H.28}$$

The logistic curve is calibrated such that 70 percent of the production occurs at the 2010 shares when volumes are below 3,000 tpd, 50 percent is at the initial shares, and 50 percent at the interpolated scenario shares when production reaches 6,000 tpd, and only 30 percent occurs at the initial shares when production reaches 9,000 tpd. The logistic function can be recalibrated by specifying different percentages for the production volumes. Figure H.10 illustrates a conversion of processes calibrated to a 50 percent conversion at 6,000 tpd and 30 percent by 9,000 tpd.

The transition function, $f(v)$, is used to calculate a weighted average of the initial 2010 production shares and the interpolated shares. Let s_{i0} be the initial share (at $t = 0$) of production process i, and let σ_{it} be the linearly interpolated, user-specified share for year t. The actual share for year t, s_{it}, is the following:

$$s_{it} = f(v)s_{i0} + (1 - f(v))\sigma_{it} \tag{H.29}$$

The third step uses the volume-dependent production shares from step two to calculate weighted average, per kilogram GHG emissions and long-run hydrogen prices.

Short-run, or current year, hydrogen prices are a function of the current hydrogen production volume. If production is less than 60 tpd, the price of hydrogen is set at $10 per kg. If production exceeds 6,000 tpd, the cost is equal to the long-run price, calculated as described in the preceding paragraphs. For production volumes between 60 and 600 tpd, the price of hydrogen is given by a power function of the production volume in the current year *t*, q_t,

$$p_t = a_{0t} q_t^{a_{1t}} \tag{H.30}$$

where a_{0t} and a_{1t} are time-dependent constant terms calibrated to the point ($10, 60 tpd) and ($p_t$, 6,000 tpd), where p_t is the long-run price for year *t* as estimated by the Process Transition submodel.

The types and number of hydrogen refueling outlets are partly determined by the production processes and partly by other assumptions specified by the model user. For subsidized stations, the user specifies the number of stations of each type for all station types. For stations added as a function of the demand for hydrogen by fuel cell vehicles on the road, the percentages that are distributed stations are determined by the production process shares, while the percentages of stations of other types are determined by the Refueling Station Transition submodel.

The model user specifies the types of stations that will be built and their capacities and utilization rates. Five types of hydrogen stations can be specified as follows:

1. Mobile refueling units,
2. Stations serviced by tube trailers carrying liquefied hydrogen,
3. Distributed steam methane reforming,
4. Distributed electrolysis, and
5. Stations connected by pipeline to centralized production plants.

Given the total demand for hydrogen in year *t*, the minimum number of stations (not including subsidized outlets) is computed as follows. Let E_t be the total estimated hydrogen demand based on the existing stock of hydrogen vehicles and their annual use and energy efficiency. Let s_{it} be the share of hydrogen assumed to be supplied by stations of type *i* in year *t*, let c_{it} be their specified capacity, and u_{it} their specified utilization rate. The minimum number of stations of type *i* in year *t* is calculated by Equation H.31.

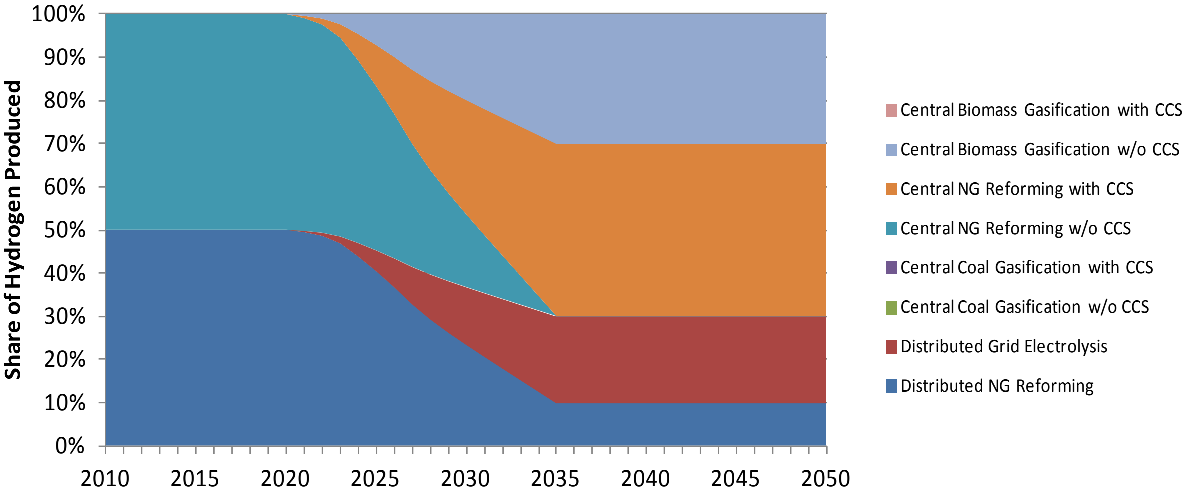

FIGURE H.10 Illustration of a transition from initial to high volume hydrogen production processes.

$$N_{it}^{\min} = \frac{E_{ht} s_{it}}{c_{it} u_{it}} \tag{H.31}$$

The demand for hydrogen vehicles in year t depends on fuel availability in year $t - 1$, and so it is not affected by stations added to supply vehicles sold in year t.

The shares of distributed steam methane reforming and electrolysis stations are also production method shares and are, therefore, specified when production methods are determined in the process transition model. The remaining three station types may be matched with any of the centralized production methods, and so the shares of these types of stations must be specified separately by the model user. These three station type shares are calculated as a function of the total volume of hydrogen production in the Refueling Stations Transition submodel. The share of station type i, s_i, is given by a multinomial logit function of the total volume of hydrogen production in year t, q_t.

$$s_{it} = \frac{e^{A_i + B_i q_t}}{\sum_{j=1}^{a} e^{A_j + B_j q_t}} \tag{H.32}$$

This model is calibrated to user-specified shares at two different values for the total hydrogen production. This gives six data points from which the six model parameters can be calibrated. For example, if the initial shares are 95 percent mobile, 2 percent tube trailer supplied, and 3 percent connected to pipeline, while the shares at 30,000 tpd hydrogen production are 40 percent mobile, 10 percent tube trailer supplied, and 50 percent pipeline, then the predicted transition would be as illustrated by Figure H.11.

The number of stations of each type is the sum of those constructed to provide the minimum amount necessary to fuel the existing stock plus subsidized infrastructure added to increase fuel availability.

The cost of the additional subsidized stations is assumed to be borne either by hydrogen supplying companies or by the government, or both, and therefore does not affect the market price of hydrogen. It is, however, counted as a social cost of the transition.

H.2.4.2 Natural Gas

Natural gas infrastructure is handled in the same way as hydrogen infrastructure, except that it is much simpler. Because natural gas is already nearly ubiquitous, there is no need to model alternative production processes for natural gas. Only one type and size of natural gas refueling station is represented. Like the modeling of hydrogen, sales of natural gas vehicles automatically induce a sufficient number of natural gas stations to refuel the vehicles on the road. Additional natural gas stations can be specified to increase fuel availability, and these stations are assumed to be subsidized either by the government or fuel suppliers, or a combination of the two. The capital costs of natural gas stations are accounted for separately so that they can be tracked.

H.2.4.3 Electricity

Infrastructure for EVs is divided into the following three categories:

1. Level 2 home chargers,
2. Level 2 public chargers, and
3. Level 3 public chargers (or DC fast chargers).

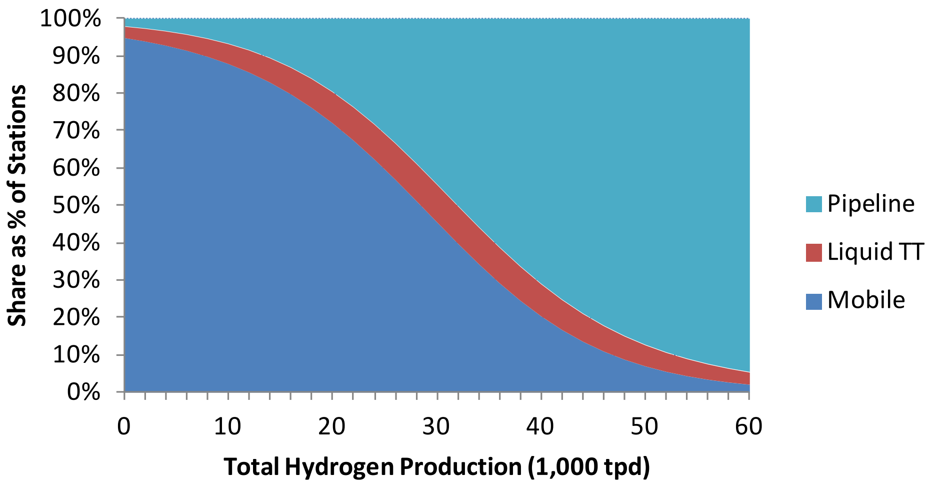

FIGURE H.11 Sample evolution of hydrogen station type shares as market expands.

The model user must specify how many of each type will be installed per PHEV sold and per BEV sold. For example, one might assume one level 2 home charger, 0.1 public level 2 chargers, and 0.01 public level 3 chargers per BEV. The number of public level 2 and level 3 chargers per PHEV may also be specified. Different ratios of chargers to vehicles may be specified for 2010, 2030, and 2050; ratios for intervening years are linearly interpolated. The total number of chargers of each type is equal to the number of BEVs and PHEVs on the road times the assumed numbers of chargers per vehicle, summed over vehicle technology types. The user may also specify charger costs for the years 2010, 2030, and 2050. Intervening year costs are linearly interpolated. The infrastructure capital cost in year t is the product of the cost per charger times the change in the number of chargers from year $t-1$ to year t. If the number of chargers decreases from $t-1$ to t, the capital cost for year t is zero.

The capital costs of home chargers are assumed to be paid for by the customer and included in the purchase price of an EV. The cost of public chargers is not added to the cost of grid-connected vehicles—it may or may not be included in the cost of electricity. If it is not included in the cost of electricity, the cost of public chargers is assumed to be a subsidy. In either case, infrastructure costs are accounted for and reported separately so that they can be tracked.

H.2.5 Policy Options

The LAVE-Trans model allows easy implementation of several policies that are designed to promote low-GHG emitting and high-fuel-efficient vehicle technologies, including feebates, an indexed highway user fee and fuel taxes. These policies are in addition to subsidies or mandates for vehicles or fuels.

H.2.5.1 Fuel Tax

Optional fuel taxes (e.g., \$/gge) are calculated as the social cost of GHG emissions and oil dependence per unit of energy use by energy type. The model user can specify the cost of per unit of emissions (\$/mmtCO2e) from four predefined scenarios. The current version of the model only defines one scenario for the cost of oil dependence (\$/barrel).

H.2.5.2 Feebates

Feebates are fiscal policies that provide rebates to the purchase of new vehicles with low-GHG emissions/high energy efficiency and charge fees for the purchase of new vehicles with high-GHG emissions/low energy efficiency. Two feebate schemes are implemented. FeebatesA is designed to reflect social willingness to pay for GHG and petroleum reduction. First, for each vehicle technology, its lifetime GHG emissions and petroleum use are calculated, as well as corresponding social cost of emissions and oil dependence. Then, the value of fees or rebates for a technology is the difference between the lifetime social cost associated with this technology and the sales weighted average social cost for all technologies. FeebatesB, on the other hand, is designed to reflect fuel costs that are not considered by consumers when making purchase decisions. Uncounted lifetime fuel costs for each technology are calculated, and the value of fees or rebates is the difference between a technology's uncounted fuel cost and the sales weighted average of uncounted fuel costs.

In the case that a fuel tax is also selected by users as one policy implemented in the model, the model will adjust the value of feebates by only considering social cost of GHG emissions and oil dependence that is not included in the fuel tax. Note that consumers are assumed to undervalue fuel costs (the payback period and discount rate can be specified by model users). Thus, the fuel tax accounts for that portion of the full social costs of GHG emissions and petroleum not included within the consumers' payback period. The remainder of social cost is reflected in the feebates so that the combined effect of the feebates and fuel taxes equals and does not exceed the vehicle's total private and social costs.

H.2.5.3 Indexed Highway User Fees

With the increase of vehicle energy efficiency, revenue from highway users collected via motor fuel taxes will decline because the existing taxes levied per unit of energy used are fixed (excise taxes). The model allows implementation of an indexed highway user fee for all fuels by scaling up current gasoline tax over time when fleet energy efficiency increases. Let q be the initial highway user fee and e be fleet average energy efficiency (e.g., MJ/km). If q_0 is the initial rate and e_0 is the initial energy efficiency, the tax rate in year t depends on the energy efficiency in year t, e_t, as follows:

$$q_t = q_0\left(\frac{e_0}{e_t}\right) \tag{H.33}$$

H.2.6 Outputs

A model run produces estimates of vehicle sales and stocks by technology type, vehicle use, energy use by vehicle and energy types, GHG emissions and petroleum use by technology type, infrastructure costs, costs of explicit and implicit subsidies, and the impacts of technology and policy changes on consumers' surplus.[9] It is expected that a base case incorporating assumed changes in vehicle and fuel technologies will be run first, followed by a policy case that includes additional actions to increase the uptake of low carbon and low petroleum technologies, thereby generating societal benefits in the forms of reduced petroleum consumption and GHG emissions. Five spreadsheets hold the resulting projections.

The Current Case spreadsheet contains summary calculations for the data and parameters currently active in the model. It includes the following tables and associated graphs:

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[9] Consumers' surplus is a monetized measure of consumer well-being, or satisfaction. It represents the economic value consumers perceive in a particular state of affairs.

1. Costs,
2. Greenhouse gas emissions and rates of GHG emissions by vehicle technology and energy type,
3. Energy use by vehicle technology and energy type,
4. Vehicle stock by technology type,
5. New vehicle sales and market shares by technology type,
6. Revenues from vehicle sales by technology type,
7. Vehicle kilometers of travel by technology type,
8. The average energy efficiency of vehicles in us by technology type,
9. The average energy efficiency of new vehicle sales by technology type,
10. Fuel carbon intensity,
11. Fuel prices and fuel taxes, and
12. Annual investment cost for producing and distributing alternative fuels.

The cost data include the total costs of infrastructure for EVs, hydrogen vehicles, and subsidies for infrastructure deployment. Fuel subsidies, vehicle subsides and the change in consumers' surplus area also included. Changes in consumers' surplus are calculated using the method of Small and Rosen (1981).

The Base Case worksheet contains the same output data as the Current Case worksheet but for a case that has been saved for the purpose of comparing it with the Current Case. Similarly, the BAU Case worksheet also contains the same format of output data but for the BAU Case.

The *Costs-Benefits* worksheet contrasts the Current Case and the Base Case worksheet results. The quantities of GHG and petroleum reductions are the year-by-year differences between the Base Case and the Current Case. Costs are total consumers' surplus changes and total subsidies. In general, providing subsidies will increase consumers' surplus, but typically by less than the subsidies themselves, which are counted as costs. Assumed social values per ton of CO_2 reduction and per barrel of petroleum reduction are multiplied by the quantities reduced to obtain measures of the societal value of the current case. Monetary values are then discounted by a user-supplied societal discount rate and summed to yield a total net present value (NPV) of the current case. The NPV constitutes a summary measure of merit of the Current Case scenario.

The Output worksheet contains more summary tables and figures, which are in the similar format to VISION results.

H.2.7 Input Data and Parameters

A large amount of input data is required to execute a scenario. Most key parameters and assumptions are contained in the Parameter Input worksheet. Switches that define vehicle and fuel technology scenarios and starting year of policy options are included in Scenario Assumption worksheet. Price elasticities of vehicle choice are entered in the Choice Parameters worksheet. Data for the Business As Usual projection (number of households, vehicles sales, energy prices, and vehicle travel) are contained in the INPUT USA.[10] Data on the costs of alternative fuels and their GHG emissions to be used in scenarios are contained in the Fuel Input worksheet. If a VISION model run is to be matched, the VISION projections are entered in the VISION worksheet.

Key parameters and assumptions have been collected into the following 10 tables in the Parameter Input worksheet:

1. Conversion factors,
2. Parameters determining consumer values,
3. Parameters determining vehicle production costs,

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[10] Typically, the BAU projection data are obtained from EIA AEO projections.

4. Vehicle attributes,
5. Assumptions about infrastructure for electric vehicles,
6. Assumptions about infrastructure for CNG vehicles,
7. Assumptions about infrastructure for hydrogen,
8. Vehicle price subsidies/taxes,
9. Fuel subsidies, taxes and prices, and
10. Specification of a scenario of advanced technology market success in the rest of the United States.

The parameters and assumptions in these tables are described below, as are their locations in the Parameter Input worksheet. In general, data and parameters that require user input are colored in green.

H.2.7.1 Parameters Determining Consumer Values for Vehicle Attributes

Parameters that determine the value consumers place on vehicle attributes are specified in lines 28-59 (highlighted in orange).

1. *Choice diversity parameter* should be between 0 and 1; it determines the value of make and model diversity to consumers.
2. *Value of time,* in $/hr, is a key determinant of the value of range and fuel availability.
3. *PHEV value of public recharging* is specified by two parameters: one is the present dollar value per vehicle of full availability of public recharging, the other describes the rate of increase in value as recharging availability approaches that of gasoline stations (illustrative graph provided).
4. *BEV range and recharging values:*
    a. *Range anxiety*—the first parameter represents the hypothetical cost of a 0 km range, the second the rate of decrease with increasing range (illustrative graph provided).
    b. *Value of public recharging*—present dollar value per vehicle of full availability and parameter describing rate of increase as availability approaches that of gasoline.
5. *Fuel availability multiplier* is the combined value of national, regional, and local fuel availability relative to only local availability.
6. *Consumer discount rates and payback periods* define the time period over which car buyers consider future fuel savings and their annual discount rates, as well as the corresponding assumptions for full social value.

H.2.7.2 Parameters Affecting Vehicle Production

Parameters that determine scale economies, learning rates, and the numbers of makes and models of each type of vehicle technology can be specified in rows 62-74.

1. *Make model volume* specifies the average production volume (1,000s) for a vehicle platform (one platform may support several makes and models).
2. *Economical scale* specifies the production volume (1,000s) at which full scale economies are achieved.
3. *Minimum scale of production* limits scale diseconomies to no more than this value divided by the economical scale raised to the power of the scale elasticity.
4. *Scale elasticity* determines the rate at which production costs fall with production volume.
5. *Progress ratio* determines the reduction in costs with each doubling of cumulative production.

6. *Rate of technological change* allows the user to specify an exogenous annual rate of reduction in the cost of each vehicle technology. However, in no case will the price of technology fall below its specified long-run, high-volume, learned-out cost. Default is 0.1 percent per year.
7. *Minimum sales*—the chief function of this parameter is to prevent division by zero errors; default is 1 unit per year.
8. *Number of makes and models in base year* calibrates the diversity of choice function.

H.2.7.3 Vehicle Attributes

Important vehicle attributes are located in rows 76-144. This begins with RPEs for all 10 vehicle types for 2010, 2020, 2030, 2040, and 2050. The values are not entered here, however, but are transferred here automatically from the Scenario Assumptions worksheet. The prices represent full volume (at optimal scale) production, including full learning by doing, at a particular point in time. They represent a hypothetical long-run average cost and reflect the status of the technology at that time.

Next are three data items for each vehicle technology that determine vehicle usage rates by age of vehicle. The first is the average annual kilometers for a new (0-year-old) vehicle, and the second is the rate of decrease in use with age. A rebound elasticity (percent change in annual miles per vehicle for a 1 percent increase in energy cost per mile) can also be entered.

These data are followed by annual maintenance costs, specified in dollars per vehicle per year. For comparison, the American Automobile Association estimates annual maintenance costs at $0.05 per mile for an average car. If the average car travels 10,000 miles per year, the average maintenance cost would be $500 per vehicle.

The next data items are vehicle efficiency in MJ/km for 2010, 2020, 2030, 2040, and 2050. This is followed by on-board energy storage capacity in gallons of gasoline equivalent for 2010, 2030, and 2050. Both of these data tables are transferred automatically by vehicle technology choices made in the Scenario Assumptions worksheet.

The final data are refueling times in hours per refueling event. For BEVs this is only the time required to plug in the vehicle. The effect of longer recharging time is accounted for in the cost of limited range, described above in Section H.2.7.1 of consumer value parameters.

H.2.7.4 Electric Recharging Infrastructure

Key parameter inputs for electricity infrastructure are located in rows 146-183 of the Input Parameters worksheet (highlighted in light green). One may specify the number of level 1 or level 2 home chargers per PHEV and per EV sold and the number of level 2 and level 3 (DC fast) chargers for public recharging per vehicle sold. This requires that a fixed number of chargers be sold for every EV sold. The costs are accumulated as infrastructure costs. The cost of home chargers may be added to the price of a PHEV or EV, or may be amortized in the cost of electricity to recharge the vehicle. Next, one may specify how many EVs can be served by a public charger compared to how many vehicles can be served by a gasoline station. This number determines the relative effectiveness of public and private recharging infrastructure in providing recharging opportunities for EVs. Next, one may specify the fraction of PHEV energy use that will be electricity in 2010, 2030, and 2050 for passenger cars and light trucks, separately. Intervening years are linearly interpolated. Finally, one may specify the equipment and installation costs of level 1, 2, and 3 chargers for home or public use.

H.2.7.5 CNG Vehicle Refueling Infrastructure

Infrastructure assumptions for CNV vehicles are to be specified in rows 185-192. These assumptions concern refueling station capacities, capital and operation costs, lifetime of stations, and discount rates, which are used in calculating equivalent annual costs as well as station utilization rate. Additional stations can be specified in row 192 to increase CNG availability in early years.

H.2.7.6 Hydrogen Refueling Infrastructure

Infrastructure assumptions for hydrogen are contained in rows 194-249. In rows 194-203, one can enter capacities, capital, and operation costs, as well as assumptions for calculating equivalent annual costs for four types of hydrogen refueling stations: (1) mobile, (2) distributed steam methane reformer, (3) distributed electrolysis, and (4) pipeline connected. Row 205 contains the current number of gasoline refueling outlets, which serves as a reference point for full fuel availability. As hydrogen vehicles are added to the fleet, the model will add hydrogen production and refueling infrastructure, according to assumptions about the shares of production by process, the shares of stations by type, and utilization rates contained in rows 245-249. Additional stations may be added to increase hydrogen availability in early years by specifying numbers of stations by year in rows 206-210. The cost of these stations is accumulated and added to the subsidy costs but they do not affect the price of hydrogen. The added stations decrease the cost of fuel availability for hydrogen vehicles, making the vehicles more attractive to consumers.

H.2.7.7 Vehicle Subsidies

Subsidies for vehicles and fuels can be specified in rows 253-265 and in rows 273-285. Vehicle subsidies must be provided separately for passenger cars and light trucks, by technology type by year. Vehicle subsidies are specified as negative numbers (taxes as positive numbers) in dollars per vehicle. Existing federal subsidies are automatically included. Subsidies in rows 273-285 should be entered first so that model’s predictions of HEV, PHEV, and BEV sales in 2010, 2011, and 2012 are matched to their real world sales. Then, additional subsidies can be specified in rows 253-265 for the purpose of promoting low-carbon vehicle technologies. Existing subsidies, i.e., tax credits for alternative fuel vehicles, are included in rows 458-475. Tax credits are $7,500 for an all-electric drive vehicle and up to $7,500 for a PHEV, depending on battery capacity, to be phased out when a manufacturer has sold 200,000 vehicles that qualify for the subsidy. The default assumptions are that five manufacturers will participate, and so the effect is approximated by phasing out the subsidies after 1 million qualifying vehicles have been sold. Net vehicle subsidies, the sum of all three kinds of subsidies, are calculated in rows 288-300.

H.2.7.8 Fuel Subsidies, Taxes and Prices

Fuel subsidies, in rows 302-311, are to be provided in native units ($/gallon, $/kWh, $/kg) and are automatically converted to dollars per megajoule. Next, the model calculates fuel tax that reflects the social cost of oil dependence and GHG emissions according to user’s choice of fuel tax starting year (as specified in cell D51 of Scenario Assumption worksheet). Net fuel subsidies, i.e., the sum of fuel tax, fuel subsidies, and indexed highway use fee, are calculated as well. The last row of this section contains net fuel prices as perceived by consumers.

H.2.7.9 Rest of World Advanced Technology Market Scenarios

Production of advanced vehicle technologies in the rest of the world is also relevant to the US market, and vice versa. Economies of scale, diversity of choice, risk perception, and technological progress are affected by developments not only in North America but the entire world. At present, an exogenous global vehicle sales scenario may be specified on rows 329-341 by entering market shares for 2015, 2020, 2030, 2040, and 2050. Intervening years are automatically interpolated and combined with a global vehicle sales forecast, which must be entered in the Input World worksheet. Given the importance of these assumptions, a more powerful and convenient scenario generator is needed—one that either choose among pre-defined scenarios or one that allows for flexible and convenient definition of new scenarios for major world regions (i.e., the European Union, China, Japan, and so on).

H.2.8 How to Run the Model

The LAVE-Trans model is implemented as an Excel Workbook with embedded macros. All that is required to run the model is Microsoft Office Excel software. The model is comprised of 25 worksheets that perform different functions. Executing a run requires use of at least five of the following worksheets: Scenario Assumptions, Parameter Input, Current Case, Costs-Benefits, and Output.

H.2.8.1 Scenario Definition

The Scenario Assumptions worksheet provides a convenient means of defining vehicle and fuel technology scenarios. The user may choose among seven general scenarios:

1. Business as usual (BAU),
2. Reference (R),
3. Mixed (M),
4. Efficiency,
5. Battery electric and plug-in hybrid electric (EV),
6. Hydrogen fuel cell (FCEV), and
7. Compressed natural gas (CNG).

The LAVE-Trans does not model FCEV and CNG simultaneously but uses the scenario name to switch between FCEV and CNG. The scenario names are also used when the model is operated to match VISION market shares, with each scenario storing market shares of a similar VISION scenario. Additionally, scenario names are used to store the share and amount of biofuels in gasoline blend, which may be scenario specific.

Next, assumptions for each of the six vehicle technologies may be set at Business-As-Usual (BAU), E (Expected Progress), O (Optimistic Progress), or R (Reference) levels. These switches select among the predefined vehicle cost and energy efficiency scenarios. Note that vehicle technologies should be set as BAU for BAU Case and R for Reference Case. Vehicle technologies for other scenarios should be selected from E and O.

The attributes of gasoline, hydrogen, electricity, and natural gas may be chosen from among the following alternatives:

1. *Gasoline blend:* R (moderate biofuel use) versus H (intensive blending of drop-in biofuels),
2. *Electricity:* R (AEO Reference Case projections of GHG intensity and price) versus L (low-carbon scenario),

3. *Hydrogen:* R (low-cost hydrogen), CCS (low-carbon hydrogen with carbon sequestration) and L (very low carbon hydrogen),
4. *CNG:* At present only one scenario has been defined, and
5. *Thermochemical biofuel:* R (default assumption for biofuel price and carbon content), CCS (biofuel with carbon sequestration).

One of the four social costs of carbon emissions produced by the Interagency Working Group (2010) may be chosen. At present there is only one social cost of petroleum projection; it begins at $25/bbl and declines to $20 per barrel by 2050.

Next is a section dedicated to policy options. Various policies are considered in the model, including indexed highway user fee, existing alternative fuel tax credits, feebates that reflect social cost of oil dependence and GHG emissions, feebates reflecting additional fuel savings that are not considered in consumer purchase decisions, and carbon tax (i.e., the fuel tax reflecting social cost of oil dependence and GHG emissions). The user can choose the starting year for all these policies. All policies, except indexed highway user fee, are phased in over a period of 5 years.

H.2.8.2 User Control

The model has several control buttons which are associated with Excel Macros.

1. Controls in Scenario Assumption Sheet (rows 32-41):
   - *Clear*. The corresponding macro simply zeros out any subsidies (including vehicle, infrastructure and fuel subsidies) that may have been entered previously.
   - *Clear and calibration.* The corresponding macro first zeros out all subsidies and then calibrates the total LDV sales to match the AEO projection located in the Input USA worksheet. The current version of the model contains projections from the 2011 AEO Reference Case. The macro also saves results in Current Case worksheet to Base Case worksheet.
   - *VKT calibration.* The corresponding macro calibrates total VKT to match the AEO projection of total LDV travel. It then saves results in Current Case worksheet to BAU Case worksheet.
2. Controls in Current Case worksheet (rows 1-7):
   - *Save Base Case.* The corresponding macro copies all the results in Current Case worksheet to the Base Case worksheet. Later, when the user changes data and assumptions, the difference between Current Case and saved Base Case is reflected in Costs-Benefits worksheet.
   - *Save BAU Case.* The corresponding macro copies all the results in Current Case worksheet to BAU Case worksheet. Some of BAU Case results are used in Output worksheet.
3. Controls in Costs and Benefits worksheet (rows 1-5 and 165-174):
   - *Update NPV.* This button needs to be clicked in order to get correct net present value estimates when fuel taxes are being used. The corresponding Macro calculates consumer surplus loss due to fuel taxes (carbon tax and the indexed highway user fee).
   - *Five "Match" buttons.* These controls are used to match market shares from VISION model. For example, the Match PHEV&EV button works to match PHEV and EV shares from VISION; the Match ADV button works to match PHEV, EV, and FCEV shares from VISION.

H.2.8.3 Step-by-Step Instructions

1. *Scenario Definition*
   Define a scenario according to the instructions in Section a.
2. *BAU Case Calibration*
   Skip this step if the case you are creating is not the BAU Case.

   The model must be calibrated if you are creating a new or revising an existing BAU Case.

   Go to the Parameter Input worksheet. Choose subsidy values for HEV, PHEV, and BEV cars in rows 276 to 278 to match historic sales.

   Go to the Scenario Assumption worksheet. First click on the Clear & Calibrate button and then the VKT Calibration button. These controls will calibrate BAU total LDV sales and VKT to match the 2011 AEO Reference Case. The model will generally not reach full convergence after calibrating sales and VKT only once. These two calibrations should be repeated 1 more time to insure that both BAU total sales and VKT equal AEO sales and VKT.

   After calibration, results in the Current Case, Base Case, and BAU Case worksheets are identical. Total net present value (NPV) in cell B46 of the Costs-Benefits worksheet should be zero.
3. *Run a Non-BAU Case*
   Click Clear button in Scenario Assumption worksheet to remove all subsidies (including vehicle, infrastructure and fuel subsidies). The summary results are presented in the Current Case worksheet. Summary tables and graphs are also presented in the Output worksheet, in a format similar to VISION model output.

   Clicking on the Save Base Case button copies summary model results in the Current Case worksheet to the Base Case worksheet. Check that the total NPV in cell B46 of the Costs-Benefits worksheet is zero. This means that both the Base Case and the Current Case are identical, and one is ready to specify a Policy Case. Changes to the model will now affect the Current Case but not the Base Case.

   The user may now change the value of subsidies for vehicles or fuels, or specify the provision of additional infrastructure for alternative fuel vehicles (relevant Excel ranges: Car Subsidies, Truck Subsidies, Fuel Subsidies, "H2_Station_Subsidies, NG_Station_Subsidies"). The effects of these policies will be calculated by the model and shown in the Current Case worksheet. Users may also want to check other worksheets (e.g., Vehicle Choice, Vehicle Sales, Vehicle Stock, Vehicle use, Energy use) for raw and intermediate results.

   The Costs-Benefits worksheet contains calculations reflecting the differences between the Current Case and Base Case results and also calculates GHG emissions and petroleum consumption reductions compared to BAU Case.
4. *Match VISION Market Shares*
   This capability makes use of the goal seek function of Excel. Users are required to input market shares to be matched, generally taken from VISION model outputs. The model calculates the vehicle subsidies needed to match the specified shares.

   Enter the shares to be matched in range D93:G97 (named range: Share_Target) of the Costs-Benefits worksheet. Click on the appropriate Match Case button (e.g., Match FCEV) in the Costs-Benefits worksheet to match FCEV shares. Vehicle subsidies are calculated and shown in C255:C265 (named range: Car Subsidies, Truck Subsidies) of the Parameter Input worksheet. This routine will estimate required subsidies only for the technology(ies) whose shares are being matched.

   It is possible to manually input subsidy values for other technologies (not being matched) and then run the Match routine to match VISION market shares for a specific technology. For example, users can specify the number of subsidized hydrogen refueling stations in the Parameter Input worksheet (named range: H2_Station_Subsidies) and then run Match FCEV routine. Another example is to tax ICE vehicles and subsidize FCEVs. Users can predefine a relationship between the tax and subsidy by entering equations in the relevant cells and then running the Match FCEV routine.

5. *Solve an Optimization Model to Maximize Social Value*
   A licensed and installed version of @Risk solver software is required to run this step. Users can define an optimization model using the Evolver module of the @risk software. One example is to maximize the net present value of a Policy Case (the value in cell B46 of the Costs-Benefits worksheet) by having the solver find optimal subsidies to PHEVs and BEVs.

H.3 FUEL INVESTMENT COST SUMMARY—LAVE-TRANS MODEL

Shown below are alternative fuel infrastructure investment costs for the LAVE-Trans model scenarios outlined in Chapter 5. The costs shown reflect only the investment costs that involve building a new form of infrastructure needed to use the fuel as a transportation fuel, not those for expanding an already large and functioning infrastructure associated with its more traditional use. They are based on costs summarized in Table 3.3 in Chapter 3 and described in greater detail in Appendix G. Biofuels investment costs are those necessary to expand the number of biofuel conversion facilities. Hydrogen investment costs represent the costs of the fueling infrastructure as well as production and distribution of the fuel. CNG costs include only the infrastructure necessary to deliver CNG to the vehicle. Electric charger investment costs include both public and private infrastructure.

Table H.6 represents the annual investment costs in each scenario during the middle of the transition period. Table H.7 depicts the undiscounted sum of annual investment costs from 2010-2050 for each scenario. Table H.8 shows the cumulative fuel infrastructure investment costs in 2050 based on an annual discount rate of 2.3 percent.

TABLE H.6 Annual Investment Costs (2009$) for 2030

	Annual investment cost in 2030 ($ millions, undiscounted)						
Scenario	Hydrogen	Biofuel	CTL with CCS	GTL	CNG	Electric Chargers	TOTAL
BAU	0	0	2,017	0	0	0	2,017
Reference	0	7,626	175	133	0	10	7,945
Eff+FBSC	0	7,626	175	133	0	21	7,955
Eff+FBSC+IHUF	0	7,626	175	133	0	22	7,956
Eff+Bio+FBSC+IHUF	0	10,022	175	133	0	21	10,351
Eff+Bio w/CCS+FBSC+IHUF	Investment costs unavailable for Biofuels w/CCS						—
Eff+Intensive Pricing+LCe	0	7,626	175	133	0	14,910	22,844
PEV+FBSC+IHUF+Trans+AEOe	0	7,626	175	133	0	4,367	12,302
PEV+FBSC+IHUF+Trans+LCe	0	7,626	175	133	0	4,465	12,400
PEV(later)+FBSC+IHUF+Trans+Lce	0	7,626	175	133	0	4,757	12,691
PEV+Bio+FBSC+IHUF+Trans+Lce	0	10,022	175	133	0	4,325	14,655
FCV+FBSC+IHUF+Trans+L$H2	11,094	7,626	175	133	0	13	19,042
FCV+FBSC+IHUF+Trans+H2CCS	11,931	7,626	175	133	0	12	19,878
FCV+FBSC+IHUF+Trans+LCH2	11,874	7,626	175	133	0	12	19,821
FCV+Bio+FBSC+IHUF+Trans+LCH2	11,218	10,022	175	133	0	12	21,560
CNGV+FBSC	0	7,626	175	133	0	21	7,955
CNGV+FBSC+IHUF+Trans	0	7,626	175	133	9,003	13	16,950
CNGV+Bio+FBSC+IHUF+Trans	0	7,626	175	133	8,660	12	19,002
Eff(Opt)+FBSC	0	7,626	175	133	0	14	7,948
Eff(Opt)+Bio+FBSC+IHUF	0	10,022	175	133	0	13	10,343
PEV(Opt)+FBSC	0	7,626	175	133	0	286	8,221
PEV(Opt)+FBSC+IHUF+Trans+Lce	0	7,626	175	133	0	5,933	13,867
FCV(Opt)+FBSC	0	7,626	175	133	0	21	7,955
FCV(Opt)+FBSC+IHUF+Trans+LCH2	17,959	7,626	175	133	0	5	25,898
PEV+FCV+FBSC+IHUF+Trans+LCe+LCH2	12,590	7,626	175	133	0	1,760	22,284
PEV+FCV+Bio+FBSC+IHUF+Trans+LCe+LCH2	12,123	10,022	175	133	0	1,658	24,111

TABLE H.7 Sum Total of Annual Investment Costs (2009$) Out to 2050

	Cumulative Investment Cost in 2050 ($ billions, discounted)						
Scenario	Hydrogen	Biofuel	CTL with CCS	GTL	CNG	Electric Chargers	TOTAL
BAU	0.0	0.0	55.5	0.0	0.0	0.2	55.8
Reference	0.0	114.7	21.0	23.9	0.0	0.6	160.2
Eff+FBSC	0.0	114.7	21.0	23.9	0.0	49.8	209.4
Eff+FBSC+IHUF	0.0	114.7	21.0	23.9	0.0	57.6	217.2
Eff+Bio+FBSC+IHUF	0.0	382.2	21.0	23.9	0.0	40.4	467.5
Eff+Bio w/CCS+FBSC+IHUF	Investment costs unavailable for Biofuels w/CCS						—
Eff+Intensive Pricing+LCe	0.0	114.7	21.0	23.9	0.0	187.1	346.7
PEV+FBSC+IHUF+Trans+AEOe	0.0	114.7	21.0	23.9	0.0	128.2	287.8
PEV+FBSC+IHUF+Trans+LCe	0.0	114.7	21.0	23.9	0.0	139.0	298.6
PEV(later)+FBSC+IHUF+Trans+Lce	0.0	114.7	21.0	23.9	0.0	144.6	304.2
PEV+Bio+FBSC+IHUF+Trans+Lce	0.0	382.2	21.0	23.9	0.0	112.1	539.3
FCV+FBSC+IHUF+Trans+L$H2	214.6	114.7	21.0	23.9	0.0	14.3	388.4
FCV+FBSC+IHUF+Trans+H2CCS	243.4	114.7	21.0	23.9	0.0	9.3	412.3
FCV+FBSC+IHUF+Trans+LCH2	244.5	114.7	21.0	23.9	0.0	8.5	412.6
FCV+Bio+FBSC+IHUF+Trans+LCH2	210.1	382.2	2.6	2.0	0.0	5.8	602.7
CNGV+FBSC	0.0	114.7	21.0	23.9	0.0	49.8	209.4
CNGV+FBSC+IHUF+Trans	0.0	114.7	21.0	23.9	128.2	19.0	306.9
CNGV+Bio+FBSC+IHUF+Trans	0.0	382.2	15.8	12.0	116.7	11.0	537.6
Eff(Opt)+FBSC	0.0	114.7	21.0	23.9	0.0	20.8	180.4
Eff(Opt)+Bio+FBSC+IHUF	0.0	382.2	21.0	23.9	0.0	14.5	441.6
PEV(Opt)+FBSC	0.0	114.7	21.0	23.9	0.0	193.4	353.0
PEV(Opt)+FBSC+IHUF+Trans+Lce	0.0	114.7	21.0	23.9	0.0	287.9	447.5
FCV(Opt)+FBSC	0.0	114.7	21.0	23.9	0.0	49.8	209.4
FCV(Opt)+FBSC+IHUF+Trans+LCH2	278.9	114.7	2.6	2.0	0.0	2.3	400.4
PEV+FCV+FBSC+IHUF+Trans+LCe+LCH2	222.0	114.7	21.0	23.9	0.0	67.7	449.2
PEV+FCV+Bio+FBSC+IHUF+Trans+LCe+LCH2	195.5	349.1	2.6	2.0	0.0	59.0	608.1

TABLE H.8 Cumulative Investment Costs (2009$) Out to 2050, Discounted Annually at 2.3 Percent

	Cumulative Investment Cost in 2050 ($ billions, discounted)						
Scenario	Hydrogen	Biofuel	CTL with CCS	GTL	CNG	Electric Chargers	TOTAL
BAU	0.0	0.0	35.3	0.0	0.0	0.2	35.5
Reference	0.0	85.8	12.2	13.1	0.0	0.4	111.5
Eff+FBSC	0.0	85.8	12.2	13.1	0.0	21.9	133.0
Eff+FBSC+IHUF	0.0	85.8	12.2	13.1	0.0	25.4	136.5
Eff+Bio+FBSC+IHUF	0.0	234.8	12.2	13.1	0.0	17.8	277.9
Eff+Bio w/CCS+FBSC+IHUF	Investment costs unavailable for Biofuels w/CCS						—
Eff+Intensive Pricing+LCe	0.0	85.8	12.2	13.1	0.0	88.9	200.0
PEV+FBSC+IHUF+Trans+AEOe	0.0	85.8	12.2	13.1	0.0	71.8	182.9
PEV+FBSC+IHUF+Trans+LCe	0.0	85.8	12.2	13.1	0.0	76.0	187.1
PEV(later)+FBSC+IHUF+Trans+Lce	0.0	85.8	12.2	13.1	0.0	76.6	187.7
PEV+Bio+FBSC+IHUF+Trans+Lce	0.0	234.8	12.2	13.1	0.0	63.4	323.5
FCV+FBSC+IHUF+Trans+L$H2	122.1	85.8	12.2	13.1	0.0	6.3	239.5
FCV+FBSC+IHUF+Trans+H2CCS	137.3	85.8	12.2	13.1	0.0	4.2	252.6
FCV+FBSC+IHUF+Trans+LCH2	137.8	85.8	12.2	13.1	0.0	3.8	252.7
FCV+Bio+FBSC+IHUF+Trans+LCH2	120.6	234.8	2.0	1.5	0.0	2.7	361.5
CNGV+FBSC	0.0	85.8	12.2	13.1	0.0	21.9	133.0
CNGV+FBSC+IHUF+Trans	0.0	85.8	12.2	13.1	83.0	8.3	202.4
CNGV+Bio+FBSC+IHUF+Trans	0.0	234.8	9.7	7.4	76.4	4.9	333.2
Eff(Opt)+FBSC	0.0	85.8	12.2	13.1	0.0	9.1	120.2
Eff(Opt)+Bio+FBSC+IHUF	0.0	234.8	12.2	13.1	0.0	6.4	266.5
PEV(Opt)+FBSC	0.0	85.8	12.2	13.1	0.0	94.6	205.7
PEV(Opt)+FBSC+IHUF+Trans+Lce	0.0	85.8	12.2	13.1	0.0	156.3	267.4
FCV(Opt)+FBSC	0.0	85.8	12.2	13.1	0.0	21.9	133.0
FCV(Opt)+FBSC+IHUF+Trans+LCH2	164.3	85.8	2.0	1.5	0.0	1.1	254.6
PEV+FCV+FBSC+IHUF+Trans+LCe+LCH2	134.2	85.8	12.2	13.1	0.0	44.4	289.7
PEV+FCV+Bio+FBSC+IHUF+Trans+LCe+LCH2	120.6	219.0	2.0	1.5	0.0	40.3	383.4

H.4 MODELING OPTIMISTIC TECHNOLOGY SCENARIOS USING THE LAVE-TRANS MODEL

Optimistic technology scenarios imply breakthrough advancement of a given technology. These are taken to represent roughly a 20 percent likelihood occurrence in technological development for the respective technology. Although such advancement is less likely than the midrange assumptions, if it occurs, it changes the landscape for adoption of a technology, both in its costs and its benefits.

H.4.1 Plug-in Electric Vehicles

If the optimistic technology projections for PEVs are used together with the midrange technology projections for other vehicles, and the same policy assumptions are maintained (transitional subsidies + social cost feebates + IHUF), PEVs maintain an ever-growing share of the market, comprising two-thirds of all vehicles sold in 2050, with over half of all vehicles being BEVs (Figure H.12).

The effect of the BEVs' one-third lower usage rates can be seen by comparing Figures H.13 and H.14. BEVs comprise 43 percent of the stock of vehicles on the road but account for 32 percent of VMT.[11] While this reduces the BEVs' impact on petroleum use and GHG emissions, it also causes a small reduction in total vehicle travel.

Assuming decarbonization of the grid, the transition to PEVs in this policy case reduces petroleum consumption by an estimated 35 percent in 2030 and petroleum consumption and GHG emission by 89 and 76 percent in 2050, respectively, versus 2005 levels (Figure H.15).

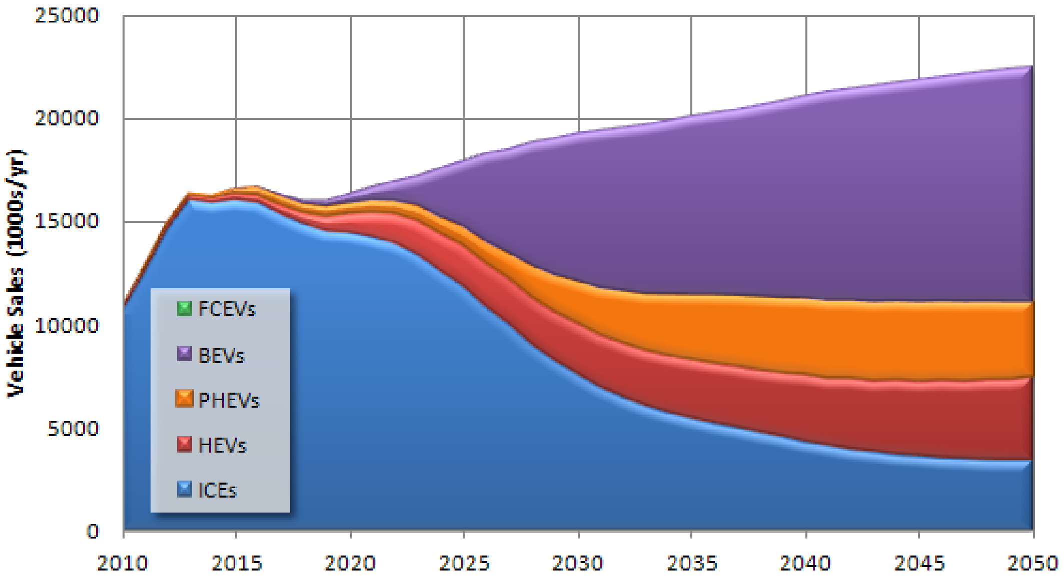

FIGURE H.12 Vehicle sales by vehicle technology assuming optimistic PEV technology estimates.

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[11] Although it is assumed that, all else equal, BEVs will be driven two-thirds as much as ICEs, usage is also affected by vehicle age and energy costs per kilometer.

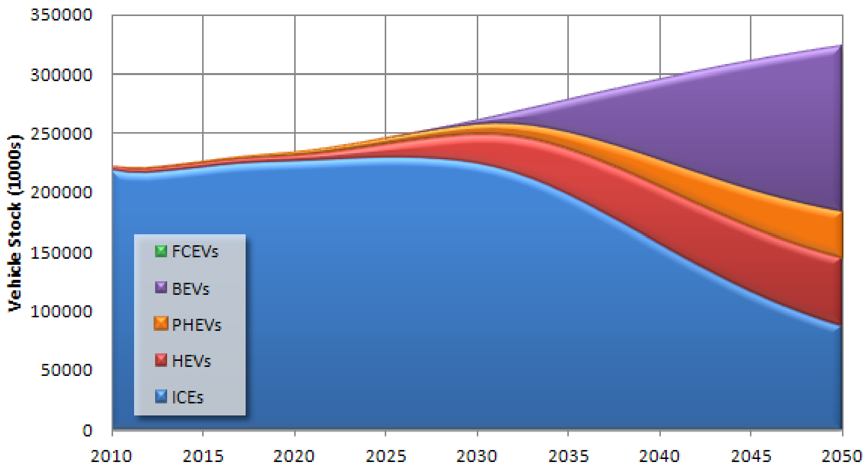

FIGURE H.13 Vehicle stock by vehicle technology assuming optimistic PEV technology estimates.

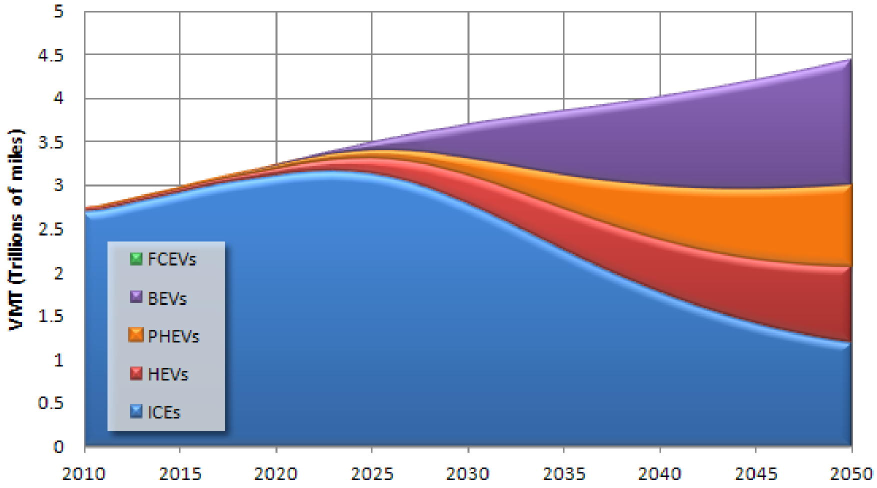

FIGURE H.14 Vehicle miles traveled by vehicle technology assuming optimistic PEV technology estimates.

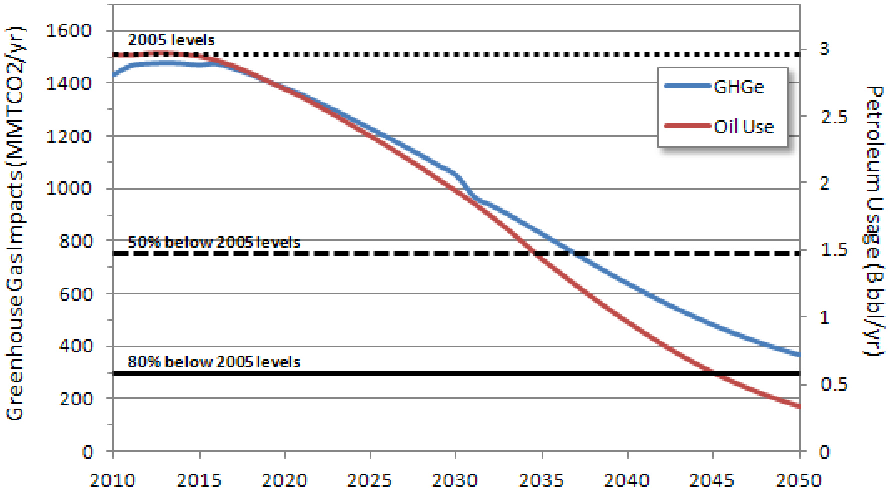

FIGURE H.15 Changes in petroleum use and GHG emissions compared to 2005 assuming optimistic PEV technology estimates and a low-GHG electric grid.

H.4.2 Hydrogen Fuel Cell Vehicles

Using the optimistic projections of FCEV technology and the midrange assumptions for all others makes it easier to introduce FCEVs (lower implicit subsidies) and increases their ultimate, sustainable market share to 75 percent. Total implied subsidies begin at $17,500 per vehicle in 2015 but can be decreased immediately thereafter. Transition subsidies can be eliminated by 2022, leaving social cost feebates in place. Sales of FCEVs are 12,000 in 2015, 22,000 in 2016 and 33,000 in 2017. In 2025, sales exceed 4 million units (Figure H.16). This transition exceeds the speed limit for transitions, with 10.0 percent of the market converting to FCEVs in 2026.

Assuming the low-carbon production of hydrogen but not advanced biofuels, this case appears to be able to meet all goals. Due to the rapid introduction of FCEVs and the substantial increase in energy efficiencies of all vehicles, petroleum use in 2030 is 50 percent lower than it was in 2005. By 2050, petroleum use by LDVs has been eliminated (replaced by 13.5 billion GGE of thermochemical biofuel and 7 billion gge of corn ethanol). GHG emissions are down 90 percent (Figure H.17).

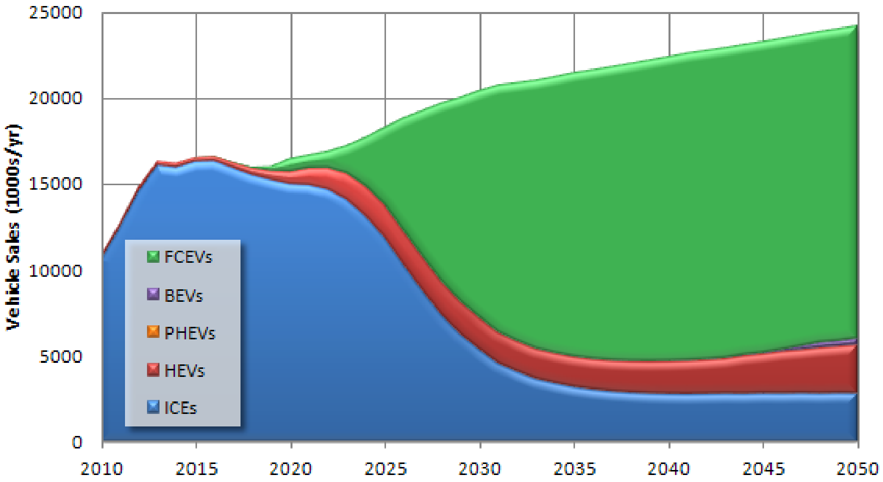

FIGURE H.16 Vehicle sales by vehicle technology assuming optimistic fuel cell electric vehicle (FCEV) technology estimates and policies that promote FCEV use.

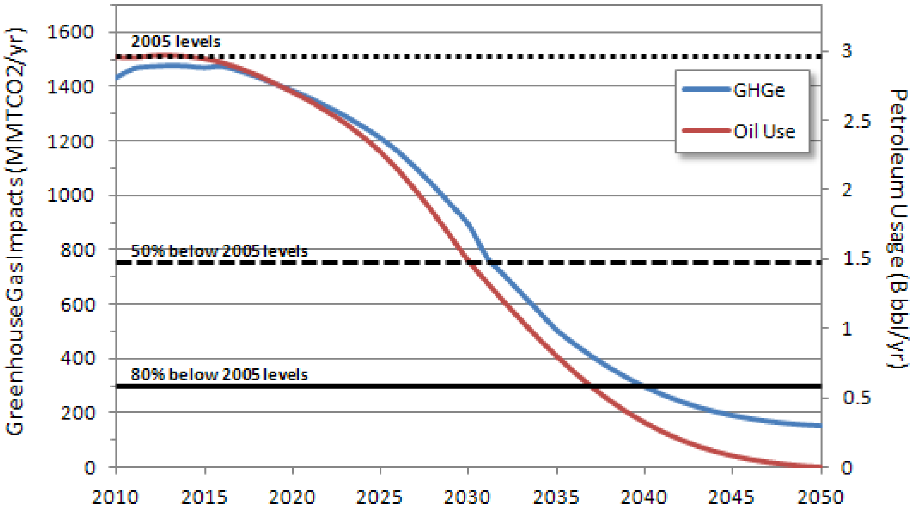

FIGURE H.17 Changes in petroleum use and GHG emissions compared to 2005 assuming optimistic FCEV technology estimates and policies that promote FCEV use.

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