Vehicle Technologies and Fuel Cell Technologies Office Research and Development Programs: Prospective Benefits Assessment for Medium- and Heavy-duty Vehicles

Energy Systems Division

About Argonne National Laboratory

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

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free at OSTI.GOV (<http://www.osti.gov/>), a service of the US Dept. of Energy's Office of Scientific and Technical Information.

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: orders@ntis.gov

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@osti.gov

Disclaimer

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

Vehicle Technologies and Fuel Cell Technologies Office Research and Development Programs: Prospective Benefits Assessment for Medium- and Heavy-duty Vehicles

by

T.S. Stephens,¹ R. Vijayagopal,¹ M. Dwyer,² A. Birky,³ and A. Rousseau¹

¹ Energy Systems Division, Argonne National Laboratory

² Energetics, Inc.

³ National Renewable Energy Laboratory

December 2019

CONTENTS

NOTATION	vii
ACKNOWLEDGEMENTS	ix
EXECUTIVE SUMMARY	1
1 INTRODUCTION	1
1.1 VTO R&D	1
1.1.1 Electrification R&D	4
1.1.2 Advanced Combustion Systems and Fuels R&D	4
1.1.3 Materials Technology R&D	5
1.2 FCTO R&D	5
2 METHODOLOGY AND ASSUMPTIONS	7
2.1 Methodology	7
2.1.1 Vehicle Size Classes and Fleet Market Segments	7
2.1.2 Models Overview	8
2.2 Assumptions	9
2.2.1 Vehicle Classes and Powertrains	9
2.2.2 Vehicle Attributes	9
2.2.3 Market Penetration and On-road Stock Modeling	21
2.3 Scenario Development	25
2.3.1 Baseline (No Program)	25
2.3.2 Program Success	25
3 INDIVIDUAL VEHICLE TECHNOLOGY BENEFITS IN ENERGY CONSUMPTION	28
4 OVERALL VTO AND FCTO BENEFITS	31
4.1 Market Penetration in Program Success and No Program Cases	31
4.2 Market Penetration in Side Cases	34
4.3 Energy and Emissions Benefits	39
5 CONCLUSIONS	46
6 REFERENCES	48
Attachment A: Autonomie Simulation Inputs	52
Attachment B: Autonomie Simulation Results	52
Attachment C: Program Success Market Penetration Inputs and Results	52
Attachment D: Program Success Stock Projections	52
Attachment E: Side Case 1 Market Penetration Results	52
Attachment F: Side Case 2 Market Penetration Results	52
Attachment G: Side Case 3 Market Penetration Results	52

FIGURES

ES-1	Projected Difference in Energy Use (All Fuel Types) between the Program Success and No Program Cases, by Size Class Bin (Negative values indicate reductions.)	ES-2
1-1	Organization of Programs in EERE's VTO and FCTO (R&D outputs from programs in boxes with bold borders are described in detail in this report)	3
2.2-1	Drive Cycles Used to Evaluate Fuel Consumption of Medium- and Heavy-Duty Cycles	10
2.2-2	Component-Specific Parameters That Affect Energy Consumption and Operating Cost Estimation	11
2.2-3	Efficiency and Cost Estimates for Medium- and Heavy-Duty Engines.....	12
2.2-4	Estimated Cost of Diesel Engine System as a Function of Engine Power.....	13
2.2-5	Estimated Cost of Diesel Engine System as a Function of Percentage Point Improvement in Engine Efficiency	14
2.2-6	Cost Estimates for Electric Machines based on VTO Goals (Both high and low cases assume the same efficiency improvements.).....	15
2.2-7	Assumed Number of Gears in Truck Transmissions.....	15
2.2-8	Battery Assumptions for Trucks.....	16
2.2-9	Fuel Cell System Efficiency and Cost Coefficients for Trucks	17
2.2-10	Hydrogen Storage Assumptions.....	17
2.2-11	Weight Reduction in Trucks Enables Increase in Payload.....	18
2.2-12	Aerodynamic Improvement Assumed in Trucks.....	19
2.2-13	Prices Assumed for Electricity and Diesel	23
2.2-14	Prices Assumed for Hydrogen.....	23
2.3-1	Fuel Economy Estimates Used in the TRUCK Model.....	26
2.3-2	Cost Estimates Used in the TRUCK Model.....	27
3-1	Overview of Energy Consumption of Trucks for Highway Driving.....	28
3-2	Comparison of Daily Energy Consumption by Various Powertrains	29
3-3	Daily Fuel Requirements in Terms of Diesel Gallon Equivalent Values.....	30
4.1-1	Projected Shares of New VMT of New Class 8 Sleeper Cab Trucks by Powertrain Type for the Program Success Case.....	31
4.1-2	Projected Shares of New VMT of New Class 7 and 8 Day Cab Trucks by Powertrain Type for the Program Success Case.....	32
4.1-3	Projected Shares of New VMT of New Class 7 and 8 Vocational Vehicles by Powertrain Type for the Program Success Case.....	32

FIGURES (CONT.)

4.1-4	Projected Shares of New VMT of New Class 4-6 Vocational Vehicles by Powertrain Type for the Program Success Case.....	33
4.1-5	Projected Shares by Powertrain Type of New VMT by New (a) Class 8 Sleeper Cab Trucks, (b) Class 7 and 8 Day Cab Trucks, (c) Class 7 and 8 Single-Unit Vocational Trucks, and (d) New Class 4–6 Vocational Vehicles for SC1, with Higher Electricity Prices.....	36
4.1-6	Projected Shares by Powertrain Type of New VMT by New (a) Class 8 Sleeper Cab Trucks, (b) Class 7 and 8 Day Cab Trucks, (c) Class 7 and 8 Single-Unit Vocational Trucks, and (d) New Class 4-6 Vocational Vehicles for SC2, with Higher Electricity Prices and No Constraints from Fuel Availability.....	37
4.1-7	Projected Shares by Powertrain Type of New VMT by New (a) Class 8 Sleeper Cab Trucks and (b) Class 7 and 8 Day Cab Trucks for SC3, with Higher Electricity Prices, No Constraints from Fuel Availability, and Higher Fuel Cell Efficiency	38
4.2-1	Projected New Vehicle Fuel Economy by Size Class, Averaged over All Powertrain Types, Program Success (solid lines) and No Program (dashed lines).....	39
4.2-2	Projected Average On-Road Stock Vehicle Fuel Economy by Size Class, Averaged over All Powertrain Types, Program Success (solid lines) and No Program (dashed lines).....	41
4.2-3	Projected Difference in Energy Use (All Fuel Types) between the Program Success and No Program Cases, by Size Class Bin (Negative values indicate reductions.)	43
4.2-4	Projected Difference in Energy Use (All Size Classes) between the Program Success and No Program Cases, for All Size Classes (Negative values indicate reductions.)	43
4.2-5	Projected Difference in Expenditures on Vehicles (All Size Classes) and Energy (All Fuels) between the Program Success and No Program Cases (Negative values indicate reductions.)	44
4.2-6	Projected Difference in WTW GHG Emissions between the Program Success and No Program Cases, for All Size Classes (Negative values indicate reductions.)	45

TABLES

ES-1	Projected Benefits of VTO and FCTO R&D in Medium- and Heavy-Duty Vehicles	ES-2
ES-2	Inputs Used in Side Cases	ES-3
2.2-1	Summary of Vehicle Classes, Vocations, and Performance Requirements Considered in This Study ^a	10
2.2-2	Manufacturing Cost Multiplier by Component and Year.....	20
2.2-3	Powertrain Choices Modeled in Each Vehicle Class/Application in the TRUCK Model.....	21
2.2-4	Example of Fuel Economy Multiplier Derivation and Application for a Single Class 8 Sleeper Cab Alternative Powertrain (Advanced Conventional, or Conventional High)	22
2.2-5	Carbon-intensity Coefficients Assumed for Hydrogen).....	24
4-2.1	Inputs Used in Side Cases	34
4-2.2	Fuel Economy and Incremental Costs of.....	35
4.2-1	Sales-Weighted Average Fuel Economy of New Vehicles by Size Class Bin, No Program Case.....	40
4.2-2	Sales-Weighted Average Fuel Economy of New Vehicles by Size Class Bin, Program Success Case.....	40
4.2-3	Average Fuel Economy of On-Road Stock of Vehicles by Size Class Bin, No Program Case.....	41
4.2-4	Average Fuel Economy of On-Road Stock of Vehicles by Size Class Bin, Program Success Case.....	42
4.2-5	Total Petroleum Use Projected for the No Program and Program Success Cases, and the Difference between the Two Cases, in MMbpd	42
4.2-6	Annual WTW GHG Emissions Projected for the No Program and Program Success Cases, and the Difference between the Two Cases, in MMmt CO ₂ -eq/yr.....	45
4.2-7	Projected Difference in GHG Emissions, Cumulative since 2020, in MMmt CO ₂ -eq/yr.....	Error! Bookmark not defined.
5-1	Projected Benefits of VTO and FCTO R&D in Medium- and Heavy-Duty Vehicles	47

NOTATION

ACRONYMS AND INITIALISMS

21CTP	21 st -Century Truck Partnership
AEO	Annual Energy Outlook
ARB	(California) Air Resources Board
Argonne	Argonne National Laboratory
BEV	battery electric vehicle
BTE	brake thermal efficiency
CI	compression-ignition
CO ₂	carbon dioxide
CO ₂ -eq	carbon dioxide equivalent
Conv	conventional
DOE	U.S. Department of Energy
EEMS	Energy Efficient Mobility Systems
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency (United States)
EVSE	electrical vehicle service equipment
FCTO	Fuel Cell Technologies Office
FCHEV	fuel cell hybrid electric vehicle
FY	fiscal year
GHG	greenhouse gas
GPRA	Government Performance and Results Act
REET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
H ₂	hydrogen
HEV	hybrid electric vehicle
ICCT	International Council on Clean Transportation
ISG	integrated starter/generator
NEMS	National Energy Modeling System
NHTSA	National Highway Transportation Safety Administration
PHEV	plug-in hybrid electric vehicle

U.S. DRIVE	United States Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
VIUS	Vehicle In-Use Survey
VMT	vehicle miles traveled
VTO	Vehicle Technologies Office
WTW	well-to-wheels

UNITS OF MEASURE

bbl	barrel(s)
bpd	barrel(s) per day
BTU	British thermal unit
gal	gallon(s)
gge	gallon gasoline equivalent
kg	kilogram(s)
kWh	kilowatt-hour(s)
lb	pound(s)
mi	mile(s)
MMbpd	million barrels per day
MMBTU	million BTU
MMmt	million metric tons
mpg	mile(s) per gallon
mpgde	miles per gallon diesel equivalent
Wh	watt hour(s)
yr	year(s)

ACKNOWLEDGEMENTS

Support and guidance by Vehicle Technologies Office (VTO) and Fuel Cell Technologies Office (FCTO) managers—Rachael Nealer and Jacob Ward of the VTO and Fred Joseck of the FCTO—were essential for completing this analysis. Amgad Elgowainy and Davie Gohlke of Argonne National Laboratory provided valuable technical assistance.

Technical targets and input for the No Program and Program Success cases came from the expert opinions of technology managers at the U.S. Department of Energy. Gurpreet Singh and Ken Howden gave input regarding the Advanced Combustion Engines and Fuels program. Brian Cunningham and Steven Boyd gave input for the Electrification program. Jerry Gibbs and Sarah Kleinbaum gave input related to the Materials Technology program. Jason Marcincoski and Fred Joseck gave input related to FCTO targets.

This page intentionally left blank.

EXECUTIVE SUMMARY

Through a diverse set of programs, the Vehicle Technologies and Fuel Cell Technologies Offices of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) invest in early-stage vehicle and fuel cell research. The Vehicle Technologies Office (VTO) and the Fuel Cell Technologies Office (FCTO) are two offices that are encompassed within EERE's Sustainable Transportation pillar. VTO conducts research and development (R&D) to provide low-cost, reliable, and efficient energy for the transportation of goods and people across America. FCTO has a comprehensive portfolio of activities that address the barriers facing the development and implementation of hydrogen and fuel cells, with the ultimate goals of decreasing our dependence on oil, reducing greenhouse gas (GHG) emissions, and enabling clean, reliable power generation through both transportation and stationary uses of hydrogen.

This report quantifies the vehicle-level and national-level benefits of successful VTO and FCTO R&D applied to medium- and heavy-duty vehicles. The benefits estimated include reductions in energy use and GHG emissions from and changes in expenditures on medium- and heavy-duty vehicles on the road in the United States through the year 2050. The potential future benefits of successfully developing and implementing these technologies were analyzed by comparing a "Program Success" case to a base case (the "No Program" case). The Program Success case represents the future with successful implementation of VTO and FCTO technologies. The No Program case represents a future in which VTO or FCTO do not contribute to these technologies after Fiscal Year (FY) 2019. Three side cases were analyzed to assess the sensitivity of the projections of market adoption to future electricity prices (including infrastructure costs), the availability of electricity and hydrogen at public stations, and fuel cell system efficiency.

Advanced vehicle technologies supported by VTO and FCTO programs can greatly increase the fuel economy of medium- and heavy-duty vehicles. As a result of EERE-supported technologies, the sales-weighted average fuel economy of the fleet of all new Class 7 and 8 trucks in the Program Success case is projected to be 1.2 times that of the trucks in the No Program case in 2035 and 1.3 times the baseline in 2050. These technologies in Classes 4–6 increase fuel economy by a factor of 1.46 in 2035 and 1.78 in 2050. The fuel economy of the entire on-road medium- and heavy-duty vehicle fleet, including all fuel types, is projected to be higher by 10%, reaching 9.1 mpgde in 2035, and by 25%, reaching 11.0 mpgde in 2050.

The resulting petroleum savings in 2050 were estimated to be 0.75 million barrels per day, and reductions in GHG emissions in 2050 were estimated to 110 million metric tons of carbon dioxide equivalent (CO₂-eq) per year. Such petroleum reductions result in significant reductions in fuel expenditure for medium- and heavy-duty vehicles, totaling approximately \$37 billion annually by 2035.

Figure ES-1 shows the difference in projected consumption of diesel fuel, electricity, and hydrogen in the No Program and Program Success cases. Negative values show the reduction in the Program Success case, relative to the No Program case.

FIGURE ES-1 Projected Difference in Energy Use (All Fuel Types) between the Program Success and No Program Cases, by Size Class Bin (Negative values indicate reductions.)

Table ES-1 lists other benefits estimated, including fuel economy improvement, reduction in annual fuel expenditures, and cumulative reductions in GHG emissions.

TABLE ES-1 Projected Benefits of VTO and FCTO R&D in Medium- and Heavy-Duty Vehicles

Metric	Year				
	2025	2030	2035	2040	2050
Oil savings rate (million bpd) ^a	0.03	0.13	0.26	0.43	0.71
New vehicle mpg improvement (percent) ^b	7	10	22	27	30
On-road stock mpg improvement (percent) ^b	1	5	10	15	23
Reduction in annual fuel expenditures (billion 2017\$/yr) ^a	2.1	7.5	13.9	22.3	35.4
Increase in annual expenditures for new vehicle purchases (billion 2017\$/yr) ^a	2.5	2.6	2.8	3.6	4.0
GHG emissions reduction, cumulative (million tons CO ₂ -eq) ^a	12	102	280	572	1480
GHG emissions reduction, annual (million tons CO ₂ -eq/yr) ^a	7	25	44	68	107

^a “Reductions” and “savings” were calculated as the difference between the results from the Program Success case (i.e., in which requested DOE funding for this technology is received and the program is successful) and the results from the baseline (No Program) case (i.e., in which there is no future DOE funding for this technology). Negative reduction values reflect increases. All cumulative metrics are based on results beginning in 2020.

^b Improvement relative to baseline (No Program) fleet in the same year.

Projections in Figure ES-1 and Table ES-1 are not intended to be predictions. Instead, they represent possible future outcomes, predicated on assumed technological progress, and other future conditions, including future electricity prices (including infrastructure costs) and future availability of electricity and hydrogen at public stations. Because we recognize that these projections are uncertain, we analyzed three side cases to assess their influence on market penetration of different powertrain technologies. The three side cases used the input assumptions listed in Table ES-2, and the sensitivity of projected new vehicle shares and shares of vehicle miles traveled (VMT) by new vehicles was analyzed. As discussed in Section 4.2, assuming higher electricity prices decreased penetration by plug-in electric vehicles (PEVs) in Classes 7 and 8 somewhat, while assuming no constraint from availability of electricity and hydrogen at public stations increased shares of fuel cell hybrid electric vehicles (FCHEVs) significantly. Assuming higher fuel cell efficiency in Classes 7 and 8, sleeper cab and day cab trucks, led to a further increase in FCHEV penetration.

The sensitivity to these inputs indicates that the projected benefits are uncertain, at least in the out-years, particularly to assumptions about hydrogen availability and fuel cell efficiency. The uncertainty in benefits is less in the near future, when other factors, especially vehicle manufacturing cost and fuel cost, are more influential. Qualitative trends in overall benefits are robust, and VTO and FCTO R&D investments in advanced vehicle technologies offer large potential benefits in increasing energy efficiency and reducing costs and GHG emissions from highway transportation in the United States.

TABLE ES-2 Inputs Used in Side Cases

Side Case	Difference from Program Success Scenario	Difference in Projected VMT by New Vehicles
SC1	Electricity prices doubled	Decreased shares of PEVs
SC2	No constraint from hydrogen or electricity availability at public stations	Increased shares of fuel cell vehicles (FCVs), little change in PEVs
SC3	Higher fuel cell efficiency in Class 7 and 8 sleeper cab and day cab trucks after 2035	Increased shares of FCVs

This page intentionally left blank.

1 INTRODUCTION

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) supports early-stage research and development (R&D) of energy efficiency and renewable energy technologies that enhance energy affordability, reliability, and resilience and strengthen U.S. energy security, economic growth, and environmental quality. The Vehicle Technologies Office (VTO) and the Fuel Cell Technologies Office (FCTO) are two offices within EERE's Sustainable Transportation pillar. VTO conducts R&D to provide low-cost, reliable, and efficient energy for the transportation of goods and people across America. FCTO has a comprehensive portfolio of activities that address the barriers facing the development and implementation of hydrogen and fuel cells, with the ultimate goals of decreasing our dependence on oil, reducing greenhouse gas (GHG) emissions, and enabling clean, reliable power generation through both transportation and stationary uses of hydrogen.

This report quantifies the vehicle-level and national-level benefits of successful VTO and FCTO R&D. The analysis in this report assesses the potential future benefits these R&D activities may have in terms of reductions in energy use and emissions from and changes in expenditures on medium- and heavy-duty vehicles on the road in the United States out to the year 2050. This report also documents the assumptions and methods used in the analysis.

The analysis documented here was performed assuming that VTO and FCTO budget levels will remain constant at recent historical levels. The technology development plans and milestones for each VTO program and for the FCTO program are presented in Section 1. Section 2 details the methodology of this benefits analysis and the assumptions made in developing two scenarios: a baseline case—"No Program"—against which to measure VTO and FCTO program benefits, and a "Program Success" case. In Section 3, results of vehicle-level modeling and analysis are discussed. Section 4 describes the benefits of the VTO and FCTO programs to the entire U.S. fleet of medium- and heavy-duty vehicles, in terms of reductions in energy use and GHG emissions, as well as some of the economic implications of these reductions the benefits attributable to VTO and FCTO R&D programs and key activities for light-, medium-, and heavy-duty vehicles. Section 5 summarizes key results. References used in support of this document are provided in Section 6.

Further details on intermediate and final results are available in spreadsheets accompanying this report.

1.1 VTO R&D

VTO funds early-stage, high-risk research to generate knowledge that industry can use to develop and implement innovative energy technologies for the efficient, reliable, and secure transportation of people and goods across America. As such:

- *R&D* focuses on reducing cost, improving energy-related performance, and minimizing emissions of a mix of medium- and long-term vehicle

technologies, including advanced batteries, electrification technologies, lightweight and propulsion materials, advanced combustion engines and fuels, and energy-efficient mobility technologies and systems.

- *Modeling, evaluation, and analysis* provide objective, publicly available data to identify the most appropriate federal investments and pathways for technology improvements, along with lessons learned for cost-effective future integration.
- *Technology integration* provides data, tools, and resources to help consumers and businesses understand their options for saving money on their transportation energy costs.

Figure 1-1 shows the technical R&D programs in VTO that provided inputs to this analysis. In addition, VTO includes programs for Energy Efficient Mobility Systems (EEMS), Technology Integration, and Analysis. Recognizing the fundamental disruption in transportation that is occurring due to the emergence of new technologies across the transportation system, and their potentially dramatic energy implications, the VTO EEMS program supports R&D to address system-level questions to advance a maximum-mobility, minimum-energy future (VTO, 2018). EEMS includes the Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Consortium, a multiyear effort at five of the DOE national laboratories that is designed to research and deliver new data, analysis, and modeling tools to help stakeholders understand the energy implications of connectivity and automation, multimodal transport of people and goods, urban mobility, advanced fueling infrastructure, and mobility decisions (Sarkar & Ward, 2016). EEMS is working with the U.S. Department of Transportation Smart City Challenge and other initiatives to examine the energy impacts of mobility systems. Living labs test new ideas, collect data, and identify best practices to inform research on energy efficiency technologies and systems.

The Technology Integration program includes a portfolio of activities that provide data, tools, and resources to help consumers and businesses understand their options for saving money on their transportation energy costs. The Data and Systems Research activity supports a broad technology portfolio that includes alternative fuels (e.g., biofuels, electricity, hydrogen, natural gas, and propane), EEMS and technologies, and other efficient advanced technologies that can reduce transportation energy costs for businesses and consumers. Data and Systems Research includes living lab activities that evaluate technology solutions under real-world conditions and generate data and lessons learned to inform future research needs. It also includes projects to disseminate data, information, and insight, as well as online tools and technical assistance to cities and regions working to implement alternative fuel and energy efficient mobility technologies and systems.

FIGURE 1-1 Organization of Programs in EERE’s VTO and FCTO (R&D outputs from programs in boxes with bold borders are described in detail in this report)

Key to the success of VTO efforts is the nationwide network of local Clean Cities coalitions that provide a boots-on-the-ground approach and significantly extend the reach of VTO efforts. The Advanced Vehicle Competitions activity provide hands-on, real-world experience to university students in the area of advanced vehicle technologies and designs. With a focus on science, technology, engineering, and math, VTO’s Advanced Vehicle Competitions support the development of a workforce trained in advanced vehicle technologies. The Legislative and Rulemaking activity implements the statutorily directed State and Alternative Fuel Provider Regulatory program, as well as alternative fuel designations, and other legislated requirements, including reports and rulemaking, analyses of impacts of other regulatory and pending legislative activities, and the implementation of legislative changes to the Energy Policy Act (EPAct) fleet activities as they occur.

Strategic public–private research partnerships with industry (e.g., United States Driving Research and Innovation for Vehicle efficiency and Energy [U.S. DRIVE] and 21st-Century Truck Partnerships [21CTP]) leverage technical expertise, prevent duplication, accelerate progress, and ensure public funding remains focused on the most critical barriers to technology commercialization. Strategic public–private partnerships with end users and other key stakeholders (e.g., Clean Cities and the National Clean Fleets Partnership) focus on overcoming market barriers and catalyzing private sector action to enable the widespread use of advanced-technology vehicles.

VTO supports the planning, execution, and communication of technological, societal, economic, and interdisciplinary analyses to inform overall VTO program planning and key technology investment decisions. The analysis activities support the planning and execution of

mission-critical technology, economic, and interdisciplinary analyses to inform and prioritize VTO technology investments and research portfolio planning. Work, analyses, and publications support essential vehicle data, modeling and simulation, and integrated and applied analysis activities, using the unique capabilities, analytical tools, and expertise resident in the national laboratory system.

1.1.1 Electrification R&D

The VTO Electrification R&D program supports research into low-cost, high-energy batteries and low-cost, efficient electric drive technologies and charging systems needed to produce efficient plug-in electric vehicles (PEVs) (including all-electric vehicles and plug-in hybrid electric vehicles [PHEVs]). Activities also include R&D of advanced thermal management technologies and advanced materials for electric drive technologies.

VTO funds early-stage research programs with partners in academia, at national laboratories, and in industry on technologies that include high-energy and high-power materials and systems that promise to significantly reduce the cost, weight, and volume of batteries. Battery R&D focuses on the technologies necessary to reduce high-volume battery costs to less than \$100/kWh and decrease charge time to 15 minutes or less, with an ultimate goal of \$80/kWh (Boyd, 2018).

The focus of the Electric Drive, Grid, and Charging R&D subprogram is on researching technologies and innovations to reduce the cost, significantly increase the power density, and improve the reliability of power electronics, electric motors, and other electric propulsion components. The electric drive cost target is \$6/kW for a 100-kW system. R&D focuses on power electronics and electric motor innovations using advanced, low-cost materials, technologies, and topologies to develop motors, inverters, chargers, and direct current (DC)/DC converters for electric drive vehicles. The subprogram will continue subcomponent R&D of high-temperature capacitors, high-power, high-density packaging of power semiconductors, and non-rare-earth magnetic materials.

1.1.2 Advanced Combustion Systems and Fuels R&D

The VTO Advanced Combustion Systems and Fuels R&D program supports research into advanced engine technologies and optimized fuel properties to improve thermal efficiency, reduce exhaust emission, and develop technologies that reduce parasitic losses to decrease petroleum use in U.S. highway transportation.

The Advanced Combustion Systems and Fuels R&D program supports research to significantly increase the efficiency of next-generation internal combustion engines that will be co-optimized with advanced fuels, fully integrating high-performance combustion and fuels R&D. The program will conduct research on fuel properties where the ultimate goal is cost-effective, performance-tailored blendstocks, including bio-derived, synthetic, and petroleum-based blendstocks to enable high-performance, efficient engines. Co-optimization of

engines and fuels as an integrated system will enable better control of future engines operating on future fuel formulations at peak efficiency for a higher portion of the drive cycles. The SuperTruck II initiative builds on the earlier VTO SuperTruck initiative and has targets of 55% or greater engine brake thermal efficiency (BTE) in real-world operation, improving freight-hauling efficiency by more than 100% over a 2009 baseline, while staying cost-effective and maintaining comparable performance (Singh, 2018). The knowledge this program generates will increase energy efficiency and improve the fuel economy of passenger and commercial vehicles entering the market. In addition to the SuperTruck II initiative, the 21CTP (or “the Partnership”) is a longstanding government/industry research collaboration with industrial partners across the commercial truck value chain and government partners with civilian and military missions. The 21CTP Research Blueprint identified reaching a peak engine efficiency of 57% as a research priority (21CTP, 2019).

1.1.3 Materials Technology R&D

The VTO Materials Technology program supports vehicle lightweighting and improved propulsion efficiency through the discovery, development, and utilization of materials and enabling technologies for light- and heavy-duty vehicles. The Materials Technology program seeks to accomplish these technical objectives through research programs with academia, national laboratories, and industry. Weight reduction R&D emphasizes the glider, which includes the body, chassis, and interior of the vehicle. A wide range of lightweight materials are considered, such as advanced high-strength steels, aluminum alloys, magnesium alloys, carbon fiber composites, and multi-material systems with performance and manufacturability that greatly exceed today’s technologies. VTO research addresses materials and manufacturing challenges that span from extraction to assembly, with an emphasis on establishing tools, capabilities, and material standards for light- and heavy-duty vehicles.

Propulsion materials R&D supports research to develop higher performance materials that can withstand increasingly extreme environments and address the future properties needs of a variety of relevant high-efficiency powertrain types, sizes, fueling concepts, and combustion modes. The activity will apply advanced characterization and multiscale computational materials methods, including high-performance computing, to accelerate innovations of cutting-edge structural and after-treatment materials for cleaner, more efficient powertrains. Goals for cost and performance targets are for material technology to enable a weight reduction in heavy-duty vehicles of 10% by 2030 and 20% by 2050 from a 2010 baseline (VTO, 2013).

1.2 FCTO R&D

Fuel cells enable highly efficient use of energy and have the potential for zero emissions when powered by renewable fuels or hydrogen produced in tandem with carbon capture and storage. FCTO R&D includes hydrogen production and delivery, hydrogen storage, and fuel cells research. The Hydrogen Production program supports R&D of technologies that will enable the long-term viability of hydrogen as an energy carrier for a diverse range of end-use applications, while the Hydrogen Delivery program addresses all hydrogen transmission and

distribution activities from the point of production to the point of dispensing (Satyapal, 2018a and 2018b). FCTO target for hydrogen cost is \$7.00/kg by 2025. The ultimate target is to reduce the total cost of hydrogen fuel to less than \$4/kg, based on targets of less than \$2/kg for production, and less than \$2/kg for delivery and dispensing (Satyapal, 2018a).

The Fuel Cells program supports research, development, and demonstration of fuel cell technologies for transportation applications, as well as stationary and early market applications, with a primary focus on reducing cost and improving durability (Satyapal, 2018a and 2018b). FCTO aims to have fuel cells usable in medium- and heavy-duty vehicles with peak system efficiency of 70% in the long term at a manufacturing cost of \$80/kW by 2030 and \$60/kW in the long term (Satyapal, 2018a).

The Hydrogen Storage program supports R&D of materials and technologies for compact, lightweight, and inexpensive storage of hydrogen (Satyapal, 2018a and 2018b). R&D on hydrogen storage inside the vehicle aims to double the energy density of hydrogen storage by 2050, while reducing the cost by more than 40%. These correspond to ultimate goals of gravimetric and volumetric storage densities of 7.8 kg H₂/kg system, at approximately \$9/kWh for a tank with a 10-kg capacity.

2 METHODOLOGY AND ASSUMPTIONS

The potential economic and environmental benefits of VTO and FCTO R&D programs were taken to be the differences in future fuel use and GHG emissions between these cases:

- The Program Success case, which assumes that there are future technology improvements and cost reductions that meet VTO and FCTO program goals; and
- The No Program case, which assumes that there is no technology improvement or cost reduction beyond 2020 due to the VTO and FCTO programs.

The No Program case was developed to represent future vehicle technology, fuel use, and GHG emissions without the effects of technology improvements brought about by the VTO and FCTO programs. Vehicle technologies are assumed to improve over time in the No Program case, but not as quickly or as much as in the Program Success case.

The potential future benefits were analyzed in three main steps. First, the No Program (baseline) case was developed, based on a modification of the Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2018 Reference case (EIA, 2018), as described in Section 2.3.1. Vehicle simulations were performed to estimate the fuel economy and costs of future vehicles and the influence of successful VTO and FCTO R&D on these, as described in Section 2.2.2. Third, market penetration models were used to develop projected sales of new, advanced-technology vehicles in selected bins of size class and vehicle applications, as described in Section 2.2.3; a stock model was used to calculate energy use and emissions by the on-road population of vehicles, as described in Section 2.3.2. This analysis captures the influence of vehicle technology costs and performance, resulting vehicle attributes, market penetration, and on-road use to estimate future energy use, emissions, and expenditures on energy and vehicles.

This analysis included the following drivetrains: advanced conventional, integrated starter/generator (ISG), hybrid electric diesel, plugin-electric hybrid (diesel), battery electric, and fuel cell hybrid electric, in vehicles of different size classes, as described in Section 2.1.1.

2.1 METHODOLOGY

2.1.1 Vehicle Size Classes and Fleet Market Segments

Recognizing differences in how vehicles of different size classes and applications are used, as well as differences in GHG and fuel economy regulations, program benefits were analyzed in subclasses consistent with the U.S. Environmental Protection Agency

(EPA)/National Highway Transportation Safety Administration (NHTSA) fuel consumption standard regulatory analysis (EPA and NHTSA, 2016a), as shown below:

- Heavy-duty trucks (weight classes 7 and 8¹),
 - Tractor sleeper cabs,
 - Tractor day cabs,
 - Vocational trucks,² and
- Medium-duty trucks (weight classes 4–6).

2.1.2 Models Overview

2.1.2.1 Vehicle Energy Consumption

Autonomie is used to evaluate the energy consumption and cost of advanced powertrain technologies in this work. It has been validated for several powertrain configurations and vehicle classes using Argonne’s Advanced Powertrain Research Facility vehicle test data (Kim et al., 2013, 2012, 2009; Rousseau et al., 2006; Cao, 2007; Rousseau, 2000; Pasquier et al., 2001). Use of Autonomie by SuperTruck participants and several other DOE-funded truck projects also demonstrated Autonomie’s applicability to heavy vehicles. Autonomie has been used in numerous studies to provide various departments of the U.S. government with guidance for future research. More than 175 companies and research entities, including major automotive companies and suppliers, use Autonomie to support their advanced vehicle development programs.

2.1.2.2 Market Penetration

The TRUCK market penetration model uses fuel economy, incremental costs, and information about alternative fuel availability to calculate annual fuel savings for advanced technology vehicles relative to baseline vehicles, and uses a payback algorithm to project market penetrations within 5,000-mile-per-year cohorts through 2050. Distributions of annual distance driven by different vehicle classes and applications were taken from the most recent Vehicle In-Use Survey (VIUS), from 2002 (U.S. Census, 2004). In addition to market penetrations of advanced-technology vehicles, the model calculates annual mileage-weighted new fleet fuel economies, average miles traveled by new vehicles by powertrain, and shares of miles that are traveled on separate fuels for bi-fuel vehicles (e.g., PHEVs).

¹ These classes are defined by the U.S. Federal Highway Administration gross vehicle weight rating (see DOE, 2019a).

² The use of the term “vocational” is adopted from EPA/NHTSA (Phase 2 medium-duty/heavy-duty GHG regulations) and refers to all trucks that are not tractors or pickups. It includes van or box-type trucks, as well as vehicles more commonly referred to as vocational (or work) trucks such as cement mixers, refuse haulers, dump trucks, and utility vehicles.

2.1.2.3 Stock Modeling

A stock-tracking model, HDStock, is used to project future miles of travel and fuel use by vehicles sold after 2010 and to estimate fuel and carbon savings, relative to the baseline case, attributable to each technology platform. This tool uses EIA's National Energy Modeling System (NEMS) methodology and parameters (i.e., sales, scrappage rates, and age-dependent mileage) and provides results consistent with AEO.

2.2 ASSUMPTIONS

2.2.1 Vehicle Classes and Powertrains

For each size class and application segment modeled (as described in Section 2.1.1), vehicles were considered to be in either centrally refueled fleets or non-centrally refueled fleets. This distinction was made because the price and availability of some fuels—and hydrogen in particular—was assumed to differ between the central and non-central fueling. The fraction of centrally refueled diesel trucks was taken to be the historical fraction within each size class given by the most recent VIUS, from 2002 (U.S. Census, 2004).

2.2.2 Vehicle Attributes

2.2.2.1 Vehicle Performance Requirements

Assumptions made in vehicle simulations were established with input from VTO and FCTO analyst and technology managers. Additional information and review of some assumptions were provided by industry experts, including industrial partners in the 21CTP, representatives from truck manufacturers, and fleet operators.

Vehicles were assumed to meet typical performance requirements for acceleration, grade speed, range, and cargo capacity, depending on size class. Cargo masses for drive cycle simulations were assumed to be the same as those the EPA and NHTSA use to establish fuel consumption standards and assess regulatory impacts (EPA and NHTSA, 2016b).

The performance capabilities that determine the engine power requirements, namely acceleration time and grade speed, are rarely advertised for these types of vehicles. Performance capabilities were estimated for each category of vehicle, assuming each vehicle was capable of following regulatory drive cycles described in Section 2.2.2.2, and assuming reasonable values for vehicle driving ranges. Summary of various vehicle classes, applications, and performance requirements are shown in Table 2.2-1.

TABLE 2.2-1 Summary of Vehicle Classes, Vocations, and Performance Requirements Considered in This Study^a

Class	Purpose	Regulatory Code	0–30 mph (s)	0–60 mph (s)	6% Grade Speed (mph)	Cruise Speed (mph)	Daily Driving Range (miles)
4	PnD ^a	Light_HD	9	30	50	70	150
6	PnD	Medium_HD	14	50	37	70	150
7	Tractor	DayCab_HR	18	66	31	65	250
7	Tractor	DayCab_MR	18	66	31	65	250
7	Tractor	DayCab_LR	18	66	31	65	250
7	Vocational	Medium_HD	18	66	25	60	200
8	Tractor	Sleeper_HR	18	60	32	65	500
8	Tractor	Sleeper_MR	18	60	32	65	500
8	Tractor	Sleeper_LR	18	60	32	65	500
8	Tractor	DayCab_HR	18	66	31	65	250
8	Tractor	DayCab_MR	18	66	31	65	250
8	Tractor	DayCab_LR	18	66	31	65	250
8	Vocational	Heavy_HD	18	66	28	60	200

^a “PnD” denotes pickup and delivery, “HD” denotes heavy-duty, “HR” denotes high roof, “MR” denotes mid roof, and “LR” denotes low roof.

2.2.2.2 Drive Cycles

The EPA has put forth compliance requirements for medium- and heavy-duty vehicles (EPA and NHTSA, 2016b). This rule specifies three drive cycles, shown in Figure 2.2-1, to evaluate different operational conditions. The transient cycle is also known as the “ARB transient cycle,” because it was developed by the California Air Resources Board (ARB).

FIGURE 2.2-1 Drive Cycles Used to Evaluate Fuel Consumption of Medium- and Heavy-Duty Cycles

In addition to these cycles, other driving conditions were simulated for sizing tests. A grade test was simulated using a proxy of the Davis Dam grade in Arizona. An 11-mile-long drive with a steady 6% grade was assumed for this test. The maximum sustainable speed was treated as the grade speed benchmark for the vehicle.

Acceleration tests were simulated to determine the time taken for the vehicle to achieve speeds of 30 and 60 mph. For heavy vehicles, acceleration times are much longer than those normally found in light-duty vehicles. Duration of the default acceleration test in Autonomie was extended to run for 100 seconds to ensure that all vehicles could be tested using the same procedure.

2.2.2.3 Component Technologies

Key performance parameters were identified for each component based on its impact on overall energy consumption of the vehicle. These are summarized in Figure 2.2-2.

Literature surveys provide a clear understanding of the present status of these parameters and VTO's goals for future years. Assumptions for the No Program scenario are guided by the improvements seen in the past few years.

FIGURE 2.2-2 Component-Specific Parameters That Affect Energy Consumption and Operating Cost Estimation

Engine. As with previous benefits analysis for medium- and heavy-duty vehicles, this study considered diesel engines for truck applications and not gasoline or natural gas engines, because EERE program goals had not been established at the time of this study.

VTO R&D has helped demonstrate 50% BTE on class 8 trucks through the SuperTruck program. The goal for the SuperTruck II project is to demonstrate a 55% BTE engine at a 65-mph cruise point on a dynamometer (DOE, 2016). With continued R&D, it may be possible to achieve 60% BTE by 2050.

We assume that the technologies developed to achieve these efficiencies will help improve smaller engines as well. Based on these targets and the goals available for smaller diesel engines from the VTO's USDRIVE Partnership (USDRIVE, 2018), assumptions were developed for the types of engines that are needed for different types of trucks. Figure 2.2-3 shows peak engine efficiencies and incremental engine costs assumed for vehicles of each size class and application for the Program Success case (shown as "High") and the No Program case (shown as "Low"). Note that the values from these Autonomie simulations were adjusted somewhat in the development of the No Program and Program Success cases, as described in Section 2.2.3.

VTO does not define the costs associated with these technologies, but EPA and NHTSA analysis of the cost implications of the Phase II rule making served as a guide to estimate the engine cost impact for achieving the efficiency targets (EPA and NHTSA, 2016a).

FIGURE 2.2-3 Efficiency and Cost Estimates for Medium- and Heavy-Duty Engines

In addition to the cost increase due to increased efficiency, the cost of the engine itself would change with the size of engine needed in the future. The engine cost was estimated based on its peak power output. The International Council on Clean Transportation (ICCT) carried out an analysis of the manufacturing cost of emission components (Posada et al., 2016), and Argonne developed a cost estimation tool to support a VTO CoOptima project. Based on the ICCT work and discussions with Argonne experts, the Argonne Autonomie team developed the cost assumptions shown in Figure 2.2-4.

These estimates provide the base cost of engine manufacture. As technology improves, we assume higher costs associated with the devices and materials used to achieve higher efficiency. EPA and NHTSA discuss several technologies and estimated costs in their regulatory impact analysis (EPA and NHTSA, 2016a). These technologies fall within the region marked in green in Figure 2.2-5. For further efficiency improvements, we assume that the cost of manufacturing the engine will gradually increase, as shown in Figure 2.2-5.

FIGURE 2.2-4 Estimated Cost of Diesel Engine System as a Function of Engine Power

FIGURE 2.2-5 Estimated Cost of Diesel Engine System as a Function of Percentage Point Improvement in Engine Efficiency

The current peak efficiency of a large, commercially available, diesel engine is about 47%. Efficiencies as high as 49% have been demonstrated in vehicles, and 21CTP has a goal of demonstrating a path to 57% efficiency under laboratory conditions by 2025. We assume, based on discussions with VTO Technology Managers, that VTO R&D could lead to peak engine efficiencies close to 60%. We estimate that the manufacturing cost increase for the engine will be close to \$5,000 when such high efficiencies are reached.

Electric Machine. VTO has set goals for light-duty electric machine cost (\$/kW) and volumetric power density (kW/L). Data from the A2Mac1 database (A2Mac1, 2019) was used to estimate the current efficiency and power density (kW/kg) values. VTO light-duty targets were used for the future cost of electric machines, shown in Figure 2.2-6, and 1% year-over-year improvement was assumed for parameters where DOE has not set a development target, including efficiency, for both Program and No Program scenarios.

FIGURE 2.2-6 Cost Estimates for Electric Machines based on VTO Goals
(Both high and low cases assume the same efficiency improvements.)

Transmission. VTO-funded programs, such as SuperTruck, have demonstrated the use of more efficient transmissions. Transmissions with more gears are assumed in the Program Success (High) case. The overall efficiency of the gearbox is already high and is expected to remain high over the years. This study assumes that all trucks are using automated manual transmissions that will ensure consistent shift performance across different types of vehicles and powertrains. Figure 2.2-7 summarizes the number of gears used in each type of vehicle.

FIGURE 2.2-7 Assumed Number of Gears in Truck Transmissions

Energy Storage. VTO supports research in batteries for light-duty vehicles, but no goals had been established for medium- and heavy-duty vehicles at the time of this study. Similar battery technologies can be used for trucks as well, but the power and energy needed will be higher—especially the energy. We assume that with much higher energy capacities needed in heavy-duty PEVs, the light-duty HEV battery goals will be applicable to ISG systems in the heavy-duty domain, HEV trucks will use technologies developed for light-duty PHEVs, and trucks with plug-in and electric powertrains will use battery technologies developed for light-duty BEVs.

Figure 2.2-8 summarizes the battery characteristics used for all trucks simulated. Battery packs for fuel cell hybrid electric vehicles (FCHEVs) were assumed to be very similar to HEV packs, so the same assumptions were made for both. Costs of PHEV and BEV battery packs were assumed to depend on energy, not power, and no power cost coefficient was used, so these values are shown as zero in these plots.

FIGURE 2.2-8 Battery Assumptions for Trucks

Fuel Cells. FCTO has put forward efficiency goals for fuel cell systems for light-duty fuel cells, and these were assumed to apply to trucks as well. However, many factors that affect the fuel cell design could change in order to meet the rigorous requirements for trucks. Higher power, longer operating time, and durability requirements will likely increase the cost of manufacturing fuel cells for trucks. FCTO provided updated cost targets for such fuel cells. Assumptions for fuel cells in medium- and heavy-duty FCHEVs are shown in Figure 2.2-9. Subsequent to this analysis FCTO published a Program Record summarizing the current status and future targets for Class 8 fuel cell trucks (FCTO, 2019), and future work will characterize the cost of trucks on the basis of these targets.

FIGURE 2.2-9 Fuel Cell System Efficiency and Cost Coefficients for Trucks

Hydrogen Storage. For the onboard storage of hydrogen, the fuel tanks in medium- and heavy-duty fuel cell vehicles (FCVs) have similar hydrogen density and potential for cost reduction to hydrogen tanks in light-duty vehicles. We assume that the amount of hydrogen that can be stored in a given mass of tank will increase with FCTO R&D, and costs will decrease, as shown in Figure 2.2-10. The cost of the tank involves a fixed cost, as well as a component proportional to the size of the tank. However, for simplicity, Figure 2.2-10 displays the cost per kilogram of hydrogen for a tank rated to store 10 kg of hydrogen.

FIGURE 2.2-10 Hydrogen Storage Assumptions

Lightweighting. Use of advanced materials and optimized design can lower the weight of trucks. A workshop conducted by DOE in 2014 provided estimates on how much weight savings can be achieved by 2050, and what cost is expected for every pound shaved from the truck. Since 2014, some of the lightweighting approaches mentioned in that report have already been deployed on trucks currently in the market, for example, the use of fiber-reinforced plastics in Class 8 tractor bodies. Cost-effective technologies tend to be adopted quickly in this segment. Future glider weight reductions and associated incremental costs assumed are shown in Figure 2.2-11.

FIGURE 2.2-11 Weight Reduction in Trucks Enables Increase in Payload

For commercial vehicles, reduction in curb weight offers two choices. One is to realize the fuel savings associated with this reduction in weight. The second option is to increase payload to compensate for the weight reduction in the glider. Although the second option may not reduce fuel consumption per vehicle-mile traveled, it provides potential operational cost savings. This savings was assumed to be \$1.37 per pound saved for Class 8 sleeper cab trucks, applied as a negative cost, based on estimated average operating cost per mile and the fraction of Class 8 trucks that operate at maximum payload.

Aerodynamic Improvements. Aerodynamic improvements are among the most cost-effective technologies available to improve the fuel economy of vehicles operating at highway speeds. Consequently, side skirts, gap reducers, and similar aftermarket devices have already been widely adopted in line-haul vehicles. More improvement in the coefficient of drag can be expected in the future with improvements in vehicle design.

The SuperTruck I initiative demonstrated that class 8 trucks can improve aerodynamics by another 20–30%. The electric semi truck from Tesla achieves an aerodynamic drag coefficient, Cd, comparable to that of passenger cars, ranging from approximately 0.3 to 0.4. Fuel-cell trucks may still need a larger frontal area for effective cooling, and may require further design improvements to achieve lower drag coefficients. To make comparisons across powertrain technologies consistent, this study assumed a retrofit approach for aerodynamic technology implementation. The body and chassis characteristics are assumed to remain the same as that of the conventional truck used as baseline. The assumptions shown in Figure 2.2-12 were developed for conventional trucks, and these were applied for all other powertrains.

FIGURE 2.2-12 Aerodynamic Improvement Assumed in Trucks

2.2.2.4 Other Cost Assumptions

The technology-specific assumptions provided the direct manufacturing costs of improving technology over the years. DOE cost targets assume components will be manufactured at a high enough volume to achieve economies of scale. Using estimated technology costs as a function of production volume reported by Schubert et al. (2015) in a report prepared for NHTSA's Phase 2 GHG and fuel economy standard regulatory analysis, cost adjustments were established for different technologies to account for production volume. Schubert et al. did not report costs for fuel cell or hydrogen storage technologies, but we assumed that these would scale similarly to battery costs. Costs for low (50,000 units), and higher cumulative production volumes were given in Schubert et al. (2015). Ratios of the costs of different technologies at the lowest and highest production volumes were used to determine direct cost multipliers.

In addition to direct manufacturing costs, there are indirect costs that depend on production volume and technology complexity/maturity. An indirect cost multiplier of 1.2 was assumed for 2035 and later, based on discussions with industry experts, but higher factors would be more appropriate for earlier years. Schubert et al. (2015) provide suggested indirect cost multipliers for different technologies, depending on complexity. Combining (multiplying) the production-dependent cost multipliers produces the factors applied to the full-scale direct manufacturing costs of the components described above to give retail costs. These factors are shown by technology and year in Table 2.2-2.

Vehicle prices were estimated by summing the component costs after applying the factors shown in Table 2.2-2 to direct, full-scale manufacturing cost estimates. Additional adjustments, of up to a few percent, were made to retail vehicle prices to align price estimates for current vehicles to current retail prices. For conventional diesel vehicles of each size class, current vehicle price information was obtained from online sources, Truck Paper (2019), and Commercial Truck Trader (2019). These prices were used as baseline (No Program) vehicle prices through 2020. These prices were assumed to increase year-over-year at the same rate as the prices estimated from the Autonomie model. Incremental prices for the alternative powertrains (from Autonomie) were applied directly to baseline vehicle prices for all years.

TABLE 2.2-2 Manufacturing Cost Multiplier by Component and Year

Component	2020 and Earlier	2025	2030	2035 and Later
Engines and emission control	1.49	1.32	1.20	1.20
Glider	1.36	1.26	1.20	1.20
Electric machines	1.95	1.55	1.29	1.20
Battery packs	2.18	1.76	1.48	1.20
Fuel cell system	2.18	1.76	1.48	1.20
Hydrogen storage	2.18	1.76	1.48	1.20
Other	1.20	1.20	1.20	1.20

2.2.3 Market Penetration and On-road Stock Modeling

2.2.3.1 TRUCK Market Penetration Modeling

As with prior benefits analyses (Stephens et al., 2017), this analysis considers only technologies developed for diesel, hybrid electric diesel, plug-in electric, and hydrogen fuel cell trucks in weight classes 4 through 8. As a result, the sales and fuel economy of class 4–8 gasoline trucks and all class 3 trucks in the Program Success case remain the same as in the baseline case. Further, no benefits are attributed to VTO or FCTO for the market penetration of natural gas and propane trucks as projected in the AEO reference case, and the Program Success case does not include additional penetration of these vehicles as a result of VTO or FCTO funding, because neither VTO nor FCTO have program targets for natural gas or propane vehicle technology.

Market shares of different powertrains were estimated using the TRUCK market penetration model for each size class/application bin. Each of these bins was modeled as a separate market. The powertrain choices modeled for each bin are listed in Table 2.2-3. The choice “Base” represents the baseline or No Program technology as described in Section 2.3.1. A blank in Table 2.2-3 indicates that a powertrain was not a choice in a given market.

Autonomie simulation results for vehicles in classes 4, 6, and 8 were used to represent each of the markets in the analysis. Classes 4 and 6 were assumed to be representative of the medium-duty truck fleet. Class 8 was assumed to be representative of the sleeper, day, and vocational heavy-duty vehicle types. Based on EIA’s 2018 AEO tractor shares estimates, which were derived from IHS Polk data from 2011, we assumed that 86% of vocational, 93% of day cabs, and 100% of sleeper cabs are class 8.

TABLE 2.2-3 Powertrain Choices Modeled in Each Vehicle Class/Application in the TRUCK Model

Class	Application	Base	Adv. Conv.	ISG	HEV	PHEV	BEV	FCHEV
8	Sleeper Cab	x	A	B	C		D	E
7 and 8	Day Cab	x	A	B		C	D	E
7 and 8	Vocational	x	A	B	C	D	E	
4–6	Vocational	x	A		B	C	D	E

The weighted Autonomie vehicle attribute outputs—specifically fuel economy (miles per gallon), cost, and charge depletion range (for plug-in vehicles) for Class 8 Sleeper, Class 7 and 8 Day Cab, Class 7 and 8 Vocational, and Class 4–6 Vocational—were processed and applied to the baseline composite vehicles before being input into the market penetration and stock modeling framework. Because the baseline composite vehicle for this round of Benefits Analysis was developed separately based on the AEO reference case new vehicle fleet, multipliers were derived from the Autonomie data to generate fuel economy values for the alternative powertrains. This ensures that the alternative powertrain fuel economy improvements over the derived baseline vehicle are proportional to Autonomie alternative powertrain fuel economy improvements over the Autonomie “Conventional Low” vehicle. An example of this process is shown in Table 2.2-4 for a single alternative powertrain (advanced conventional).

For each vehicle type, current vehicle price information was obtained from online sources, Truck Paper (2019) and Commercial Truck Trader (2019). These prices were used as baseline vehicle prices through 2020. These costs were assumed to increase year-over-year at the same rate as the costs estimated from the Autonomie model (conventional low). Incremental costs for the alternative powertrains (from Autonomie) were applied directly to this baseline.

TABLE 2.2-4 Example of Fuel Economy Multiplier Derivation and Application for a Single Class 8 Sleeper Cab Alternative Powertrain (Advanced Conventional, or Conventional High)

Year	Autonomie mpg Outputs		Multiplier	TRUCK/HDS Stock mpg Inputs	
	Conv. Low	Adv. Conv.	(Adv. Conv. / Conv. Low)	Baseline	Adv. Conv., adjusted
2025	7.17	8.27	1.15	7.81	9.01
2030	7.89	9.15	1.16	8.21	9.52
2050	7.89	10.71	1.36	8.21	11.14

2.2.3.2 Fuel Prices and Availability

The TRUCK market penetration model uses projections of fuel prices to estimate the value of future fuel savings and compare these savings to the up-front technology cost. Fuel prices for all but hydrogen fuels were taken from the AEO 2018 reference case. Prices for hydrogen for non-centrally refueled fleets were based on FCTO targets for light-duty FCHEVs. Projected prices are intended to reflect the price paid at the pump, including hydrogen production, distribution, and dispensing. Slightly lower hydrogen prices were assumed for centrally refueled fleets, which are expected to have a higher utilization of refueling equipment and correspondingly lower capital costs. Diesel prices for centrally refueled fleets were assumed to be slightly lower than non-central prices, based on the Clean Cities 2018 Alternative Fuel Price Report (DOE, 2018). Prices assumed for electricity and diesel are shown in Figure 2.2-13, and prices for hydrogen are shown in Figure 2.2-14.

FIGURE 2.2-13 Prices Assumed for Electricity and Diesel

FIGURE 2.2-14 Prices Assumed for Hydrogen

Fuels other than electricity and hydrogen were assumed to be fully available at public fuel stations and to centrally refueled fleets. Electricity and hydrogen were assumed to be fully available to centrally refueled fleets; for non-centrally refueled fleets, they were assumed to be available at a fraction of public stations. This fraction was assumed to increase over time. For electric charging stations, this fraction was based on extrapolations of historical numbers of gasoline and public charging station counts from the Alternative Fuel Data Center (DOE, 2019b). Historical station numbers for light-duty vehicle stations were used due to lack of data or projections for heavy-duty charging stations. For hydrogen, the fraction was based on scenarios used in the previous benefits analysis (Stephens et al., 2017).

2.2.3.3 On-road Stock Modeling

Market penetration projections were used as inputs to the HDStock model, along with attributes of new vehicles and fuel prices to track the on-road stock and miles traveled by size class bin and powertrain type. The HDStock model was used to estimate annual fuel use, GHG emissions, and expenditures on fuels and new vehicles for the No Program and Program Success scenarios. The HDStock model was calibrated to produce consumption results within about $\pm 1.2\%$ of the adjusted AEO reference case when the AEO new vehicle fuel economies are used as inputs.

To estimate GHG emissions, carbon-intensity coefficients (kilogram [kg] of CO₂ equivalent per million BTU) were used for each fuel type to estimate the GHG emissions associated with fuel consumption. For petroleum-based fuels, full fuel cycle coefficients from the Argonne GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model (2017 version) were used to estimate GHG emissions (Argonne, 2019). Coefficients for electricity were also taken from GREET assuming the U.S. average mix of generation types, which was assumed to change over time as projected in the AEO reference case. The same hydrogen carbon intensities from the previous benefits analysis (Stephens et al., 2017) were used, assuming that hydrogen was produced by a combination of methane reforming and electrolysis using an evolving mix of conventional and renewable electricity. Carbon intensity coefficients for electricity and hydrogen used are listed in Table 2.2-5.

TABLE 2.2-5 Carbon-intensity Coefficients Assumed for Hydrogen

Year	Carbon Intensity (kg CO ₂ -eq/MMBTU)	
2025	105.0	129.0
2030	94.5	126.2
2050	85.1	115.0

2.3 SCENARIO DEVELOPMENT

2.3.1 Baseline (No Program)

The No Program scenario represents a possible future in the absence of VTO and FCTO R&D, and thus serves as a baseline case. The fuel economies of vehicles in this baseline were derived from the AEO 2018 reference case by assessing the impact of market penetration of new technologies supported by DOE funding. EIA provided individual component technology contributions to truck fuel economy and market penetration of these technologies in the AEO 2018 reference case. In preparing the AEO, EIA calculates technology penetrations at a finer level of disaggregation (19 subclasses) than reported in the publicly available AEO output tables (3 broad categories). Therefore, the penetrations were analyzed in subclasses consistent with the EPA/NHTSA fuel consumption rules as described in Section 2.1.1.

Using the EPA regulatory baseline 2017 vehicle fuel economies for these subclasses, as documented in the AEO input files, in conjunction with the technology penetration tables, we determined the contributions of VTO-supported technologies to the reference case new fleet fuel economies. The baseline case was constructed by removing the impact of these technologies from the new fleet fuel economy after 2020, which was selected as the baseline year for the benefits analysis. No technologies were removed from the AEO reference case through 2018 to ensure that the baseline case complies with the Phase 1 rule as estimated by EIA. Note that the derived baseline case fuel economies met EPA Phase II regulations, even after removing VTO-supported technologies. Technology penetrations relative to 2017 were determined for three years: 2025, 2035, and 2050 (the last AEO projection year).

The reference case new fleet fuel economy for class 7 and 8 sleeper cab tractors increases by 29.7% between 2017 and 2050. The contribution of VTO technologies for class 7 and 8 sleeper cab tractors is estimated to be 39.6% of this improvement; therefore, the baseline case sleeper cab truck includes 60.4% of the total fuel economy increase through 2050, equivalent to a 17.9% improvement between 2017 and 2050 without VTO. VTO benefits for other classes were estimated similarly; VTO technology contributions for Class 7 and 8 day cab tractors, class 7 and 8 vocational trucks, and class 4–6 vocational trucks were estimated at 40.1%, 25%, and 32.5%, respectively. The AEO new medium (classes 4–6) and heavy (classes 7 and 8) sleeper cab, day cab, and vocational truck fuel economy projections were then modified to eliminate the VTO technology contributions using the same process.

2.3.2 Program Success

The Program Success scenario represents a future in which vehicles have VTO and FCTO technologies. The attributes from Autonomie simulations were used for vehicles in each of the market segments shown in Table 2.2-3. Classes 4 and 6 were assumed to be representative of the medium-duty truck fleet; when weighting class 4 and class 6 attributes to a single representative vehicle, the class 5 share was split evenly between classes 4 and 6. Class 8 was assumed to be representative of the sleeper, day, and vocational heavy-duty vehicle types. The

weighted Autonomie vehicle attribute outputs—specifically fuel economy (miles per gallon), cost, and charge depleting range (for plug-in vehicles) for Class 8 Sleeper, Class 7 and 8 Day, Class 7 and 8 Vocational, and Class 4–6 Vocational—were processed and applied to the baseline vehicles described in Section 2.3.1 before being used in the market penetration and stock modeling framework.

Because the baseline vehicle fuel economies were derived from the AEO reference case vehicle, and not directly from Autonomie results, multipliers were derived from the Autonomie data to generate fuel economy values for the alternative powertrains. This ensures that the alternative powertrain fuel economy improvements over the derived baseline vehicle are proportional to Autonomie alternative powertrain fuel economy improvements over the Autonomie Conventional Low vehicle.

The incremental costs and fuel economies developed as discussed above were used as inputs to the TRUCK market penetration model and are summarized in Figures 2.3-1 and 2.3-2. Note that 2020 fuel economies are not shown because VTO benefits were not attributed until 2021. In addition, note that all costs are incremental relative to the baseline truck. Except for the baseline case fuel economy, input values for intervening years were calculated using linear interpolation.

FIGURE 2.3-1 Fuel Economy Estimates Used in the TRUCK Model

FIGURE 2.3-2 Cost Estimates Used in the TRUCK Model

The TRUCK market penetration model uses projected fuel prices to estimate the value of future fuel savings and compare these savings to the up-front technology cost. Future fuel prices as described in Section 2.2.3.1 were used in this analysis.

The TRUCK model requires four additional input assumptions: discount rate, market adoption curve, fuel availability curve, and number of annual operating days. A discount rate of 7.5% was assumed here. The market adoption curve relates the adoption rate to the payback period. The curve used assumes technologies with payback periods longer than 3 years have less than 20% adoption rates, while those with payback periods shorter than 18 months have an 80% adoption rate. The fuel availability factor adjusts adoption based on the availability of alternative fuels and accounts for the influence of limited availability of a new fuel on the adoption of vehicles requiring that fuel, in this case electricity and hydrogen. Electricity and hydrogen availability for non-centrally refueled fleets were based on projections as described in Section 2.2.3.1.

3 INDIVIDUAL VEHICLE TECHNOLOGY BENEFITS IN ENERGY CONSUMPTION

Fuel consumption was estimated from simulations over all three drive cycles mentioned in Section 2.2.2.2. A summary of the fuel consumption of present-day trucks on highway driving is shown in Figure 3-1.

Figure 3-1 shows that the start-stop systems and HEV systems do not provide large fuel savings during highway driving, where there is no idling and only limited opportunity for regenerative braking. For heavy trucks, hybrid powertrains might even result in increased fuel consumption during highway driving. The lack of idle events and limited scope for regenerative braking in highway driving, when combined with the additional weight of hybrid components, results in this scenario. The potential to downsize the engine varies with the class and vocation of the truck. Due to two factors, the electrical energy consumption for PHEVs and BEVs observed here is likely to be higher than that claimed by some of the manufacturers. The first factor is the choice of drive cycle in this case. In the simulations shown here, the vehicle maintains a speed of 65 mph on varying grades. Most manufacturers state their energy consumption for an optimum steady speed on a flat road. The second factor is that the aerodynamic improvements and chassis weight assumptions for the BEVs in this study come from the baseline conventional vehicles, which means the same chassis and body were assumed for all powertrains. Truck manufacturers who are building a new vehicle have the option to design a body and chassis specifically suited to their powertrain. This factor can be considered in future simulations for VTO benefit analysis.

FIGURE 2.3-1 Overview of Energy Consumption of Trucks for Highway Driving

Each vehicle is sized for a specific application. Class 8 sleeper trucks are sized to drive 500 miles without refueling or recharging. Similarly, class 4 and 6 trucks are sized to drive 150 miles before stopping for fuel. When comparing the fuel displacement potential of these powertrains, we assume a scenario where these vehicles are driven for their full daily driving range. This forces all powertrains, including PHEVs, to use all types of onboard energy storage. ISGs, HEVs, FCHEVs, and PHEVs will achieve a charge-sustaining condition. Note that PHEVs were simulated as having electric ranges of one-half the daily driving distances listed in Table 2.2-1. PHEVs and BEVs will deplete the battery, thereby maximizing the petroleum displacement potential of each powertrain. Energy consumption was converted to diesel gallon equivalent values for comparison and shown in Figure 3-2, which displays simulated daily fuel consumption by vehicles, representative of new, production-year 2017 vehicles, under the three regulatory drive cycles.

Future improvements in powertrain components will slightly alter the relative advantages of each powertrain, but the overall trend will remain similar. This is shown in Figure 3-3, which compares daily fuel requirements for each of the three drive for future vehicles with different powertrains for each of the three drive cycles.

FIGURE 2.3-2 Comparison of Daily Energy Consumption by Various Powertrains

FIGURE 3-3 Daily Fuel Requirements in Terms of Diesel Gallon Equivalent Values

4 OVERALL VTO AND FCTO BENEFITS

4.1 MARKET PENETRATION IN PROGRAM SUCCESS AND NO PROGRAM CASES

We used the TRUCK market penetration model to develop projections of market penetration by different powertrain types within each bin of size classes and applications. Projections presented here are not intended to be predictions. Instead, they represent possible future market outcomes, predicated on assumed technological progress, and other future conditions, including fuel prices and availability of electricity and hydrogen and public stations. The TRUCK model estimated shares of VMT by new vehicles by powertrain choice; these shares are shown in Figures 4.1-1 through 4.1-4 for the four market segments: class 8 sleeper cab, class 7 and 8 day cab, class 7 and 8 vocational, and classes 4–6, respectively. These projections are for the Program Success case; in the No Program case, VMT is nearly 100% Conventional diesel. These shares include only the powertrain choices analyzed in the TRUCK market penetration model. Annual sales of other powertrains using other fuels, including conventional gasoline, gasoline HEV, compressed natural gas, liquid natural gas, and liquefied petroleum gas, were assumed to be the same in both the No Program and Program Success cases.

FIGURE 4.1-1 Projected Shares of VMT by New Class 8 Sleeper Cab Trucks by Powertrain Type for the Program Success Case

FIGURE 4.1-2 Projected Shares of VMT by New Class 7 and 8 Day Cab Trucks by Powertrain Type for the Program Success Case

FIGURE 4.1-3 Projected Shares of VMT by New Class 7 and 8 Vocational Vehicles by Powertrain Type for the Program Success Case

FIGURE 4.1-4 Projected Shares of VMT by New Class 4–6 Vocational Vehicles by Powertrain Type for the Program Success Case

For class 8 sleeper cab trucks, the diesel-powered alternative powertrains (advanced conventional, ISG, and HEV) show immediate high market penetration, reaching over 90% of sales in 2025, as shown in Figure 4.1-1. This is because the incremental costs are relatively small and sleeper trucks drive a high number of miles each year, which leads to a quick payback. The trucks with advanced conventional and ISG powertrains are very similar in both performance and cost, and therefore take an even share of the alternative powertrain market, while the HEVs are slightly more expensive (less so as time progresses) and take a smaller share. BEV market adoption is somewhat limited in this category due to their high daily mileage requirements (around 450 miles per day, on average, with many traveling further).

Class 7 and 8 day cab trucks show a similar trend in Figure 4.1-2: diesel-powered alternative powertrains penetrate quickly, reaching 80% in 2025. The lower annual miles traveled, around 30% fewer than sleeper cabs, and correspondingly slower payback, is likely a key factor in this difference. In addition, sleeper cabs gain a larger fuel economy improvement per increase in cost for the advanced conventional and ISG powertrains. In class 7 and 8 day cab trucks, advanced powertrains (advanced conventional, ISG, HEV, PHEV, BEV, and FCHEV) take nearly 90% of vehicle-miles by 2050.

Market penetration projections for class 7 and 8 vocational trucks are quite different, as shown in Figure 4.1-3. The lower market penetration by advanced powertrains in this segment is likely due to the considerably lower annual miles traveled by trucks in this class (75% lower than sleeper cabs and 65% lower than day cabs). At its lowest, the baseline truck is responsible for 41% of VMT in 2026, but it increases to about 60% and holds steady until 2050. Due to the technologies assumed to be included in the advanced conventional and hybrid electric vehicles, the fuel cost savings relative to incremental purchase costs decrease, and therefore the payback

period increases beginning in 2025. This effect, while present in the sleeper and day cab markets, is significantly stronger in the single-unit market because each truck drives a low number of miles each year. In total, advanced vehicles account for 40% of new vehicle miles in 2050, which indicates that market adoption is limited to the highest-mileage trucks.

4.2 MARKET PENETRATION IN SIDE CASES

The adoption of new vehicle technologies will be influenced by future fuel prices and availability and by future technological progress. In particular, we recognize that the electricity prices assumed for medium- and heavy-duty vehicles do not explicitly include costs of purchasing and installing charging infrastructure, and the future availability of hydrogen and electricity at public fueling and charging stations is highly uncertain. In addition, FCTO is revising the program goal for fuel cell efficiency in heavy-duty trucks, for a peak efficiency of 72% in the long term (up from 70% assumed in the Program Success case). Because we recognize that these factors are uncertain, we analyzed three side cases to assess their influence on market penetration of different powertrain technologies. The three side cases used the input assumptions listed in Table 4.2-1, and the other assumptions remain the same as in the Program Success case.

In the first side case, SC1, all inputs were the same as in the Program Success case, except that the price of electricity was doubled. That is, we assume it was twice the electricity price for the Transportation sector in the AEO 2018 reference case. We did this to gauge the sensitivity of market adoption to a higher electricity price that might include cost of purchasing and installing high-power electrical vehicle service equipment (EVSE) suitable for charging medium- and heavy-duty PEVs. No cost analysis of such EVSE costs was found in literature, but installation and operation of high-powered charging stations are known to be very costly. If all costs are amortized over the electricity delivered, the cost per kilowatt-hour can range higher by more than an order of magnitude depending on charging station utilization (Francfort et al., 2017; Muratori et al., 2019). For reasonable levels of utilization, consistent with the electricity demands in the Program Success case in the years when projected PEVs market adoption first becomes significant, an electricity price a factor two times the AEO reference case price is reasonable. This is based on one of the scenarios Muratori et al. (2019) analyzed for a station with a capacity of 4 MW and 400-kW ports. At intermediate-to-high utilization, costs are under \$0.20/kWh, which is within the range of prices assumed in SC1.

TABLE 4-2.1 Inputs Used in Side Cases

Side Case	Difference from Program Success scenario
SC1	Electricity prices doubled from AEO 2018 reference case
SC2	No constraint from hydrogen or electricity availability at public stations (full availability assumed)
SC3	Peak fuel cell efficiency in class 7 and 8 sleeper cab and day cab trucks increases from 68% in 2035 to 72% by 2050

In the second side case, SC2, in addition to the higher electricity prices, we assumed that availability of electricity and hydrogen was not a constraint to adoption of PEVs and FCVs in non-centrally refueled fleets. (Note that in the Program Success case, all fuels were assumed to be fully available to centrally refueled fleets). This was implemented in the TRUCK market penetration model by setting the availability of electricity and hydrogen to 100% for all years. This 100% availability assumption was not intended to represent ubiquitous public electric charging stations and hydrogen stations, which is not likely in the near future, but was intended to model full availability to fleets that adopt PEVs and FCVs, that is, the infrastructure was assumed to build out with PEV and FCV market adoption to remove availability as a constraint to adoption.

In the third side case, SC3, in addition to higher electricity prices and no electricity or hydrogen availability constants, we assumed that there would be higher fuel cell efficiency in class 7 and 8 sleeper cab and day cab fuel cell trucks in out-years, with peak efficiency increasing from 68% in 2035 to 72% in 2050. Autonomie simulations were run for the 2050 (lab year 2045) fuel cell trucks. Trucks were sized to match the same performance requirements as other trucks (and the same as in the Program Success and No Program cases). The increased fuel cell efficiency increased the fuel economy of these trucks and decreased the amount of hydrogen required to meet the range requirement, which resulted in smaller hydrogen tanks with concomitant reductions in vehicle weight and cost. The fuel economy values and incremental prices (above the price of a baseline conventional truck) of class 7 and 8 fuel cell trucks in 2050 (lab year 2045) are listed in Table 4.2-2.

Shares of VMT by new vehicles for each of the four market segments in SC1 are shown in Figure 4.1-5.

TABLE 4-2.2 Fuel Economy and Incremental Costs of Class 7 and 8 Fuel Cell Trucks

Size Class	70% Peak Fuel Cell Efficiency (Program Success)		72% Peak Fuel Cell Efficiency (SC3)	
	Fuel Economy (mpgde)	Incremental Cost (\$)	Fuel Economy (mpgde)	Incremental Cost (\$)
Class 8 Sleeper	11.37	9,206	11.92	\$8,237
Class 7&8 Day Cab	10.51	7,746	11.21	\$4,685

FIGURE 4.1-5 Projected Shares by Powertrain Type of New VMT by New (a) Class 8 Sleeper Cab Trucks, (b) Class 7 and 8 Day Cab Trucks, (c) Class 7 and 8 Single-Unit Vocational Trucks, and (d) New Class 4–6 Vocational Vehicles for SC1, with Higher Electricity Prices

Comparing these projections with those for the Program Success case, shown in Figures 4.1-1 through 4.1-4, we conclude that higher electricity prices have little influence up to 2035, when PEVs first show significant adoption, which is primarily in classes 4–6. The fraction of new VMT in class 4–6 vocational trucks shows a slower growth in BEV and PHEV shares than in the Program Success case, with lower PHEV shares in SC1 for all years. The BEV share grows to slightly more than that in the Program Success case, but the total share of PEVs is lower in SC1. The share of VMT by FCHEVs in SC1 is very slightly higher than in the Program Success case.

Shares of VMT by new vehicles for each of the four market segments in SC2 are shown in Figure 4.1-6.

FIGURE 4.1-6 Projected Shares by Powertrain Type of New VMT by New (a) Class 8 Sleeper Cab Trucks, (b) Class 7 and 8 Day Cab Trucks, (c) Class 7 and 8 Single-Unit Vocational Trucks, and (d) New Class 4-6 Vocational Vehicles for SC2, with Higher Electricity Prices and No Constraints from Fuel Availability

SC2 had the same high electricity prices as in SC1, but no constraints from fuel availability. VMT shares in Figure 4.1-16 for SC2 show a more rapid increase in adoption of FCHEVs in classes 7 and 8 and much higher adoption of FCHEVs in classes 4–6 after 2035. Shares of PEV are less influenced by increased fuel availability than FCHEVs.

Shares of VMT by new vehicles for each of the two market segments in SC3 are shown in Figure 4.1-7.

FIGURE 4.1-7 Projected Shares by Powertrain Type of VMT by New (a) Class 8 Sleeper Cab Trucks and (b) Class 7 and 8 Day Cab Trucks for SC3, with Higher Electricity Prices, No Constraints from Fuel Availability, and Higher Fuel Cell Efficiency

These three side cases show that the market penetration projections under the Program Success case are somewhat sensitive to the inputs examined, depending on the powertrain, market segment, and time frame. There was very little change in market penetration in any of the four market segments before 2035, when PEVs and FCHEVs showed basically no adoption. Factors such as the PEV and FCHEV purchase prices made these choices uncompetitive in the early years and were therefore much more important than availability or fuel cell efficiency.

Market adoption was sensitive to these other factors in later years. As electricity price increased, shares of PHEVs decreased, but shares of BEVs and FCHEVs showed little sensitivity. Removing the constraints of hydrogen and electricity availability from the market penetration in non-centrally refueled fleets resulted in significantly larger penetration by FCHEVs, which took shares way from the other powertrains, including PEVs. Increasing the fuel cell efficiency in class 7 and 8 FCHEVs in later years increased FCHEV adoption, particularly in those years.

These side cases showed how market penetration could differ from the Program Success projections under different assumptions about important inputs. However, these differences were significant only in the later years. Because several years are required for changes in market penetration to propagate through the on-road vehicle stock, changes in energy use and emissions by the on-road stock are moderated. The overall benefits estimated in the following sections are therefore fairly robust, and VTO and FCTO R&D investments in advanced vehicle technologies offer large potential benefits in increasing energy efficiency and reducing costs and GHG emissions from highway transportation in the United States.

4.3 ENERGY AND EMISSIONS BENEFITS

Based on the market penetration and fuel economy of new vehicles with each powertrain and within each size class, we projected the sales-weighted average fuel economy of new vehicles by size class to 2050 for the Program Success scenario. These projections are shown in Figure 4.2-1. Fuel economies are shown for both the Program Success case (solid lines) and No Program case (dashed lines).

Table 4.2-1 for the No Program case and Table 4.2-2 for the Program Success case provide fuel economies of new vehicles within each size class bin, averaged over all powertrain and fuel types. As a result of EERE-supported technologies, the sales-weighted average fuel economy of the fleet of all new class 7 and 8 trucks is projected to be up to 1.3 times that of the baseline trucks in 2035 and up to 1.4 times the baseline in 2050. These technologies in classes 4–6 increase fuel economy by a factor of 1.55 in 2035 and 1.78 in 2050 due to high market penetration of electrified powertrains.

FIGURE 4.2-1 Projected New Vehicle Fuel Economy by Size Class, Averaged over All Powertrain Types, Program Success (solid lines) and No Program (dashed lines)

TABLE 31 Sales-Weighted Average Fuel Economy of New Vehicles by Size Class Bin, No Program Case

Size	2025	2030	2035	2040	2050
Class 8 Sleeper Cab	7.05	7.44	7.45	7.44	7.45
Class 7 and 8 Day Cab	6.24	6.52	6.53	6.54	6.57
Class 7 and 8 Vocational	6.73	7.40	7.49	7.50	7.53
Class 4–6 Vocational	9.16	10.19	10.34	10.38	10.43
All ^a	9.14	9.84	9.91	9.94	10.04

^a Averages shown for “All” include class 3 trucks, for which AEO reference case fuel economies were assumed for both No Program and Program Success cases.

TABLE 42 Sales-Weighted Average Fuel Economy of New Vehicles by Size Class Bin, Program Success Case

Size	2025	2030	2035	2040	2050
Class 8 Sleeper Cab	8.03	8.57	9.15	9.33	9.66
Class 7 and 8 Day Cab	7.09	7.45	8.13	8.36	8.90
Class 7 and 8 Vocational	7.36	8.36	8.59	8.68	8.98
Class 4–6 Vocational	9.71	11.40	15.15	17.40	18.56
All ^a	9.80	10.81	12.07	12.62	13.11

^a Averages shown for “All” includes class 3 trucks, for which AEO reference case fuel economies were assumed for both No Program and Program Success cases.

As the market penetration of more efficient new vehicles increases, the average fuel economy of the on-road stock is projected to increase significantly. Averages of fuel economy of the on-road stock of each size class bins for the Program Success and No Program cases are shown in Figure 4.2-2 in miles per gallon of diesel equivalent (mpgde, where 1 gal of diesel was taken to be equivalent to 138,700 BTU). The fuel economy of the entire on-road medium- and heavy-duty vehicle fleet, including all fuel types, is projected to be higher by 10%, increasing from 8.3 to 9.1 mpgde in 2035, and by 25% from 8.8 to 11.0 mpgde in 2050. These projections are shown in Table 4.2-3 for the No Program case and Table 4.2-4 for the Program Success case.

FIGURE 4.2-2 Projected Average On-Road Stock Vehicle Fuel Economy by Size Class, Averaged over All Powertrain Types, Program Success (solid lines) and No Program (dashed lines)

TABLE 53 Average Fuel Economy of On-Road Stock of Vehicles by Size Class Bin, No Program Case

Size	2025	2030	2035	2040	2050
Class 8 Sleeper Cab	6.39	6.88	7.20	7.35	7.43
Class 7 and 8 Day Cab	5.73	6.04	6.27	6.41	6.54
Class 7 and 8 Vocational	5.89	6.26	6.66	6.98	7.35
Class 4–6 Vocational	8.15	8.83	9.46	9.86	10.27
All ^a	7.26	7.85	8.29	8.57	8.83

^a Averages shown for “All” includes class 3 trucks, for which AEO reference case fuel economies were assumed for both No Program and Program Success cases.

TABLE 64 Average Fuel Economy of On-Road Stock of Vehicles by Size Class Bin, Program Success Case

Size	2025	2030	2035	2040	2050
Class 8 Sleeper Cab	6.52	7.43	8.22	8.79	9.34
Class 7 and 8 Day Cab	5.83	6.43	6.95	7.38	7.98
Class 7 and 8 Vocational	5.94	6.49	7.07	7.53	8.12
Class 4–6 Vocational	8.23	9.17	10.45	12.27	15.52
All ^a	7.36	8.25	9.10	9.88	10.90

^a Averages shown for “All” includes class 3 trucks, for which AEO reference case fuel economies were assumed for both No Program and Program Success cases.

The higher average fuel economies in the Program Success case result in lower energy consumption than the No Program case. Figure 4.2-3 shows the projected reduction in energy used (all fuel types) by the on-road stock of vehicles by size class bin. Projected differences in fuel use by fuel type (Program Success minus No Program) for all vehicle size classes are shown in Figure 4.2-4. The large decrease in petroleum use is due to both the increasing efficiency of vehicles that use petroleum and the adoption of vehicles that use little (PHEVs) or no (BEVs and FCHEVs) petroleum. Petroleum use and savings (shown as negative values) projections for all size classes are shown in Table 4-2.5, in millions of barrels of petroleum per day (MMbpd).

TABLE 75 Total Petroleum Use Projected for the No Program and Program Success Cases, and the Difference between the Two Cases, in MMbpd

Case	2025	2030	2035	2040	2050
Program Success	2.34	2.16	2.05	1.95	1.83
No Program	2.34	2.33	2.29	2.38	2.54
Difference	-0.03	-0.13	-0.26	-0.43	-0.71

Adoption of advanced vehicle technologies results in significant fuel savings. Putting additional technologies and more advanced technologies on vehicles increases their purchase prices. However, as shown in Figure 4.2-5, the reduction in expenditures on fuel (all types) greatly outweighs the increase in vehicle expenditures. Figure 4.2-5 shows the difference in total spending per year (Program Success minus No Program) on vehicles, fuels, and the net change (the sum of changes in vehicles and fuel expenditures).

FIGURE 4.2-3 Projected Difference in Energy Use (All Fuel Types) between the Program Success and No Program Cases, by Size Class Bin (Negative values indicate reductions.)

FIGURE 4.2-4 Projected Difference in Energy Use (All Size Classes) between the Program Success and No Program Cases, for All Size Classes (Negative values indicate reductions.)

FIGURE 4.2-5 Projected Difference in Expenditures on Vehicles (All Size Classes), Energy (All Fuels), and Net (Sum of Vehicles and Fuels) between the Program Success and No Program Cases (Negative values indicate reductions.)

Reductions in energy use are accompanied by reduction in CO₂ emissions. Well-to-wheels (WTW) GHG emissions projected for the entire medium- and heavy-duty fleet for the Program Success and No Program cases are listed in Table 4.2-6, which shows a reduction in annual emissions of 111 MMmtCO₂-eq/yr in 2050. Projected changes in WTW GHG emissions for each size class bin are plotted in Figure 4.2-6, showing large reductions in most size classes. Reductions in class 8 sleeper cab trucks are due to the large VMT of this segment, which leads to large emission reductions when more efficient vehicle technologies are adopted. Large reductions in classes 4–6 are due to the high market penetration of BEVs and FCHEVs. The modest emission reduction projected for class 7 and 8 vocational trucks for which VMT and market penetration of advanced powertrains are due largely to the limited miles traveled by these trucks and modest market penetration of advanced powertrains in this segment.

Overall, decreasing the costs of advanced vehicle technologies leads to adoption of these technologies in the most heavily used market segments with concomitant reduction in GHG emissions. Reductions in emissions are projected to increase as more advanced-technology vehicles penetrate the on-road vehicle stock, resulting in accelerating reduction in cumulative GHG emissions since 2020, which are listed in Table 4.2-7 (negative values indicate reductions).

TABLE 86 Annual WTW GHG Emissions Projected for the No Program and Program Success Cases, and the Difference between the Two Cases, in MMmt CO₂-eq/yr

Case	2025	2030	2035	2040	2050
Program Success	497.3	475.7	462.0	456.3	467.4
No Program	504.4	500.3	506.2	524.0	574.7
Difference	-7.1	-24.6	-44.2	-67.7	-107.2

FIGURE 4.2-6 Projected Difference in WTW GHG Emissions between the Program Success and No Program Cases, for All Size Classes (Negative values indicate reductions.)

TABLE 97 Projected Difference in GHG Emissions, Cumulative since 2020, in MMmt CO₂-eq/yr

Year	Difference
2025	-12.0
2030	101.9
2035	-280.0
2040	-572.2
2050	-1,475.9

5 CONCLUSIONS

New technologies being developed under VTO and FCTO R&D programs can be used to improve the cost-effectiveness and fuel economy of medium- and heavy-duty vehicles that will be on the road in the future. Research in advanced vehicle and fuel cell technologies could have significant economic value in the U.S. transportation sector, help fleets save money, and increase the diversity of energy sources for on-road transportation. The estimated benefits of successfully developing and implementing these technologies (the Program Success case) relative to the base case (the No Program case), show that benefits of this government investment are significant.

Comparing the Program Success and No Program cases, the average fuel economy of the entire on-road medium- and heavy-duty vehicle fleet, including all fuel types, is projected to be improved by VTO and FCTO technologies by 10% from 8.3 to 9.1 mpgde in 2035 and by 25% from 8.8 to 11.0 mpgde in 2050. The resulting annual petroleum savings in 2035 were estimated to be 0.27 and 0.75 MMbpd in 2050. Such petroleum reductions result in significant reductions in fuel expenditure for medium- and heavy-duty vehicles, reaching nearly \$14 billion annually by 2035.

Reductions in annual GHG emissions were estimated to be 45 million metric tons (MMmt) of CO₂-eq per year in 2035 and 111 MMmt CO₂-eq per year in 2050. Cumulative reduction in WTW GHG emissions since 2020 are projected to reach over 1500 MMmt CO₂-eq in 2050.

Table 5-1 lists the projected benefits of VTO and VTO technologies if successfully developed and implemented in medium- and heavy-duty vehicles. The potential benefits are large and show the value of these technologies and their potential to make transportation more affordable, efficient, and sustainable.

The sensitivity to these inputs indicates that the projected benefits are uncertain, at least in the out-years, particularly to assumptions about hydrogen availability and fuel cell efficiency. The sensitivity of benefits to these uncertain inputs is lower in the near future, when other factors, especially vehicle manufacturing cost and fuel cost, are more influential. Qualitative trends in overall benefits are robust, and VTO and FCTO R&D investments in advanced vehicle technologies offer large potential benefits in increasing energy efficiency and reducing costs and GHG emissions from highway transportation in the United States.

TABLE 5-1 Projected Benefits of VTO and FCTO R&D in Medium- and Heavy-Duty Vehicles

Metric	Year				
	2025	2030	2035	2040	2050
Oil savings rate (million bpd) ^a	0.03	0.13	0.26	0.43	0.71
New vehicle mpg improvement (percent) ^b	7	10	22	27	30
On-road stock mpg improvement (percent) ^b	1	5	10	15	23
Reduction in annual fuel expenditures (billion 2017\$/yr) ^a	2.1	7.5	13.9	22.3	35.4
Increase in annual expenditures for new vehicle purchases (billion 2017\$/yr) ^a	2.5	2.6	2.8	3.6	4.0
GHG emissions reduction, cumulative (million tons CO ₂ -eq) ^a	12	102	280	572	1,480
GHG emissions reduction, annual (million tons CO ₂ -eq/yr) ^a	7	25	44	68	107

^a “Reductions” and “savings” were calculated as the difference between the results from the Program Success case (i.e., in which requested DOE funding for this technology is received and the program is successful) and the results from the baseline (No Program) case (i.e., in which there is no future DOE funding for this technology). Negative reduction values reflect increases. All cumulative metrics are based on results beginning in 2020.

^b Improvement relative to baseline (No Program) fleet in the same year.

6 REFERENCES

21CTP, (21st Century Truck Partnership), 2019, “21st Century Truck Partnership Research Blueprint,” February, U.S. Department of Energy, <https://www.energy.gov/eere/vehicles/downloads/21st-century-truck-partnership-research-blueprint>, accessed March 23, 2020.

A2Mac1, 2019, Your Global Partner for Benchmarking, <https://portal.a2mac1.com/> (password required).

Argonne National Laboratory (Argonne), 2019, GREET® Model: The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model, available at <https://greet.es.anl.gov/>, Accessed March 23, 2020.

Boyd, S., 2018, “Batteries and Electrification R&D Overview,” presented at U.S. Department of Energy VTO Annual Merit Review and Peer Evaluation, Washington, DC,

Cao, Q.P., 2007, “PHEV Hymotion Prius Model Validation and Control Improvements,” presented at 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, Dec.

Commercial Truck Trader, 2019, <https://www.commercialtrucktrader.com/>, accessed March 23, 2020.

DOE (U.S. Department of Energy), 2016, Notice of Intent DE-FOA-0001484 to Issue Funding Opportunity Announcement entitled Advanced Systems Level Technology Development, Integration and Demonstration for Efficient Class 8 Trucks (Supertruck II), https://www.grants.gov/net/grants_gov_display.php?program=DE-FOA-0001484, accessed March 23, 2020.

DOE, 2018, “Clean Cities Alternative Fuel Price Report, April 2018,” https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_april_2018.pdf, accessed March 23, 2020.

DOE, 2019a, “Vehicle Weight Classes & Categories, <https://afdc.energy.gov/data/10380>, accessed March 23, 2020.

DOE, 2019b, Alternative Fuels Data Center, <https://afdc.energy.gov/>, accessed March 23, 2020.

Energy Information agency (EIA), 2018, *Annual Energy Outlook 2018 with Projections to 2050*, Energy Information Administration, Office of Integrated Analysis and Forecasting. Washington, DC: U.S. Department of Energy. <https://www.eia.gov/outlooks/archive/aeo18/>, accessed March 23, 2020.

EPA (U.S. Environmental Protection Agency) and NHTSA (National Highway Transportation Safety Administration), 2016a, “Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2: Regulatory Impact Analysis,”

August, EPA-420-R-16-900, <https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-greenhouse-gas-emissions-and-fuel-efficiency>, accessed May 16, 2019.

EPA and NHTSA, 2016b, “Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2: Final Rule,” October 25, <https://www.govinfo.gov/content/pkg/FR-2016-10-25/pdf/2016-21203.pdf>, accessed May 17, 2019.

FCTO (Fuel Cell Technology Office U.S. Department of Energy), 2019, Subsection of the Electrified Powertrain Roadmap, Technical Targets for Hydrogen-Fueled Long-Haul Tractor-Trailer Trucks,” Program Record 19006, December 12, https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf, accessed March 23, 2020.

Francfort, J., Salisbury, S., Smart, J., Garetson, T., and Karner, D., 2017, “Considerations for Corridor and Community DC Fast Charging Complex System Design,” Idaho National laboratory report INL/EXT-17-40829, May, <https://avt.inl.gov/sites/default/files/pdf/reports/DCFCCChargingComplexSystemDesign.pdf>, accessed March 23, 2020.

Kim, N., Carlson, R., Jehlik, F., and Rousseau, A., 2009, “Tahoe HEV Model Development in PSAT,” SAE paper 2009-01-1307, presented at SAE World Congress & Exhibition, Detroit, MI, April, <http://papers.sae.org/2009-01-1307>.

Kim N., Rousseau, A., and Duoba, M., 2013, “Validating Volt PHEV Model with Dynamometer Test Data using Autonomie,” Report No. SAE 2013-01-1458, SAE World Congress, Detroit, MI, April.

Kim N., Rousseau, A., and Rask, E., 2012, “Autonomie Model Validation with Test Data for 2010 Toyota Prius,” Report No. SAE 2012-01-1040, SAE World Congress, Detroit, MI, April.

Muratori, M., Kontou, E., and Eichman, J., 2019, “Electricity rates for electric vehicle direct current fast charging in the United States,” *Renewable and Sustainable Energy Reviews*, 113, 109235.

Posada F., Chambliss, S., and Blumberg, K., 2016, “Costs of emission Reduction Technologies for Heavy-Duty Diesel Vehicles,” White paper by the International Council on Clean Transportation, Feb, <http://www.theicct.org/publications/costs-emission-reduction-technologies-heavy-duty-diesel-vehicles>, accessed March 23, 2020.

Pasquier, M., Duoba, M., and Rousseau, A., 2001, “Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedure,” presented at 18th International Electric Vehicle Symposium (EVS18), Berlin, Germany, Oct. 20–24, https://www.autonomie.net/publications/papers_validation.html, accessed March 23, 2020.

Rousseau, A., 2000, “Simulation and Validation of Hybrid Electric Vehicles Using Autonomie,” presented at 3rd Global Powertrain Congress, Detroit, MI, June 6–8.

Rousseau, A., Kwon, J., Sharer, P., Pagerit, S., and Duoba, M., 2006, “Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using AUTONOMIE,” SAE paper 2006-01-0667, presented at SAE World Congress and Exhibition, Detroit, MI, April, <http://papers.sae.org/2006-01-0667>.

Sarkar, R., and J. Ward, 2016, “DOE SMART Mobility: Systems and Modeling for Accelerated Research in Transportation,” pp. 39–52 in *Road Vehicle Automation 3*, Springer International Publishing.

Satyapal, S., 2018a, “Hydrogen and Fuel Cell Program Overview,” presented at U.S. Department of Energy FCTO Annual Merit Review and Peer Evaluation, Washington, D.C., https://www.hydrogen.energy.gov/pdfs/review18/01_satyapal_plenary_2018_amr.pdf, accessed March 23, 2020.

Satyapal, S., 2018b, “2017 Annual Progress Report: DOE Hydrogen and Fuel Cells Program,” Report DOE/GO-102017-5042, <https://www.osti.gov/biblio/1460682-annual-progress-report-doe-hydrogen-fuel-cells-program>, accessed March 23, 2020.

Schubert, R., Chan, M., and Law, K., 2015, *Commercial medium- and heavy-duty truck fuel efficiency technology cost study*, Report No. DOT HS 812 177, June, Washington, DC: National Highway Traffic Safety Administration, https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812194_commercialmdhdtruckfuel efficiency.pdf, accessed March 23, 2020.

Singh, G., 2018, “Overview: Advanced Combustion Systems and Fuels R&D,” presented at U.S. Department of Energy VTO Annual Merit Review and Peer Evaluation, Washington, DC, <https://www.energy.gov/eere/vehicles/downloads/vehicle-technologies-office-merit-review-2018-doe-advanced-combustion>, accessed March 23, 2020.

Stephens, T.S., A. Birky, and D. Gohlke, 2017, Vehicle Technologies and Fuel Cell Technologies Office Research and Development Programs: Prospective Benefits Assessment Report for Fiscal Year 2018, ANL/ESD-17/22, Argonne National Laboratory, Argonne, IL, November, <https://www.osti.gov/scitech/biblio/1410412-vehicle-technologies-fuel-cell-technologies-office-research-development-programs-prospective-benefits-assessment-report-fiscal-year>, accessed March 23, 2020.

Truck Paper, 2019, <https://www.truckpaper.com/>, accessed March 23, 2020.

U.S. Census, undated, “Vehicle Inventory and Use Survey (VIUS),” <https://www.census.gov/econ/overview/se0501.html>, accessed March 23, 2020.

USDRIIVE, 2018, Advanced Combustion and Emission Control Roadmap, March, https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC_TT_Roadmap_2018.pdf, accessed March 23, 2020.

VTO (Vehicle Technologies Office, U.S. Department of Energy), 2013, Workshop Report: Trucks and Heavy-duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, Feb.

VTO, 2018, Energy Efficient Mobility Systems, 2017 Annual Progress Report, <https://www.energy.gov/eere/vehicles/downloads/energy-efficient-mobility-systems-fy2017-annual-progress-report>, accessed March 23, 2020.

Attachment A: Autonomie Simulation Inputs: ANL - MDHD - VTO_FCTO - Autonomie Main Assumptions - 20190828_release.xlsx

Attachment B: Autonomie Simulation Results: ANL - MDHD - VTO_FCTO - Autonomie Main Results - 20190822.xlsx

Attachment C: Program Success Market Penetration Inputs and Results: TRUCK_results-Final.xlsx

Attachment D: Program Success Stock Projections: BenefitsCalculation_Final_for distribution_092019.xlsx

Attachment E: Side Case 1 Market Penetration Results: sc01_doublefuelprice_results_v2.xlsx

Attachment F: Side Case 2 Market Penetration Results: sc02_doublefuelprice_fuelav_results_v2.xlsx

Attachment G: Side Case 3 Market Penetration Results: sc03_doublefuelprice_fuelav_h2mpg_results_v2.xlsx

Attachments are available on-line: doi 10.17038/ES/1616250.

Energy Systems Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4832

www.anl.gov

U.S. DEPARTMENT OF
ENERGY

Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.