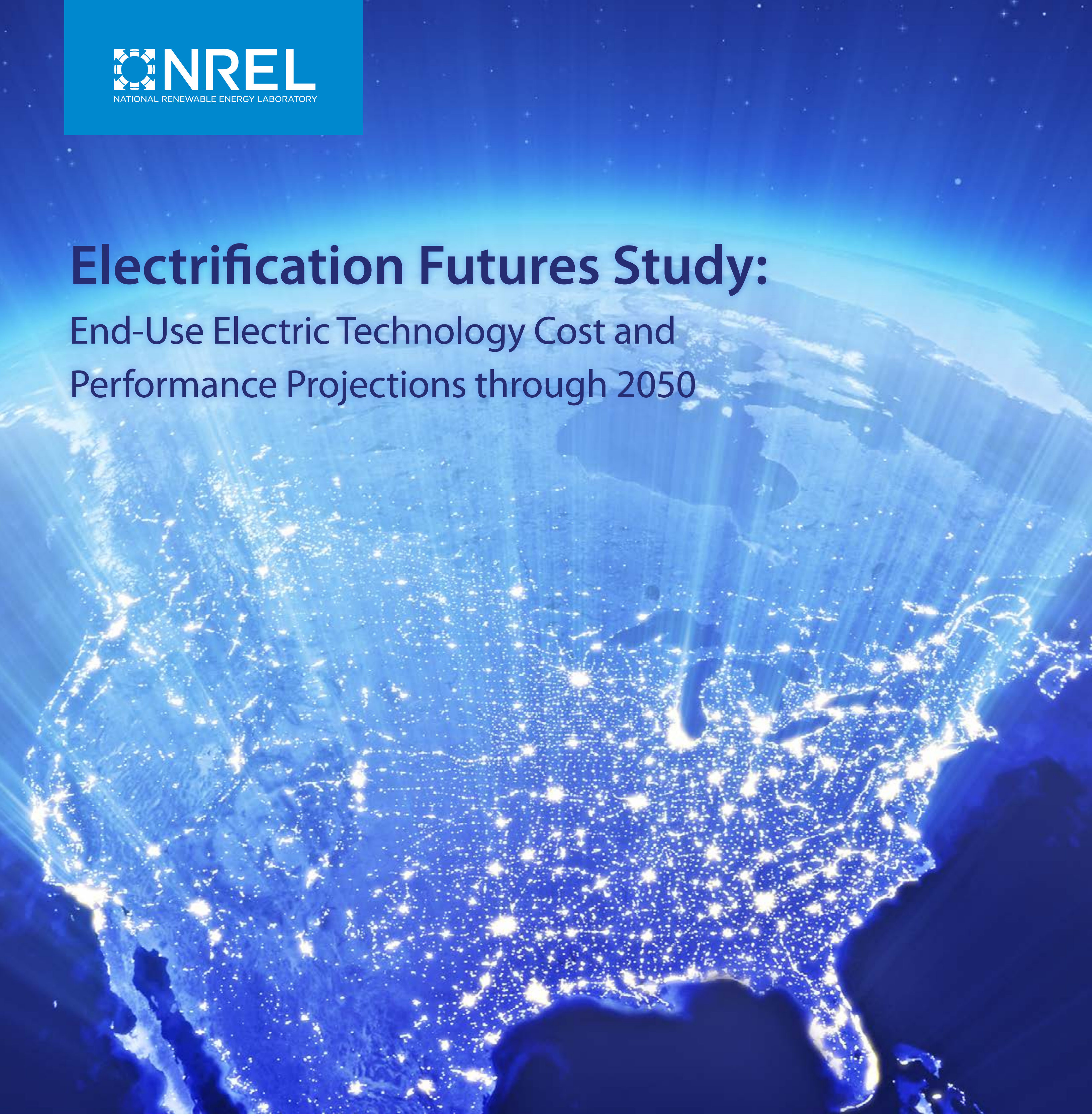

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Electrification Futures Study:

End-Use Electric Technology Cost and Performance Projections through 2050

Paige Jadun, Colin McMillan, Daniel Steinberg,
Matteo Muratori, Laura Vimmerstedt, and Trieu Mai

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Preface

This report is the first in a series of Electrification Futures Study (EFS) publications. The EFS is a multi-year research project to explore widespread electrification in the future energy system of the United States. More specifically, the EFS is designed to examine electric technology advancement and adoption for end uses in all major economic sectors as well as electricity consumption growth and load profiles, future power system infrastructure development and operations, and the economic and environmental implications of widespread electrification. Because of the expansive scope and the multi-year duration of the study, research findings and supporting data will be published as a series of reports, with each report released on its own timeframe. The table below shows the various research topics planned for examination under the EFS and how this report fits with the other components of the study.

Topic	Relation to this Report
Electric technology cost and performance projections	*Presented in this report*
Electrification demand-side adoption scenarios	Energy and electricity use estimates rely on technology efficiencies presented in this report.
Electric system supply-side scenarios	Indirect relation from consumption results
Electricity consumption patterns	Electricity usage amounts and spatiotemporal patterns rely on technology characteristics presented in this report.
Electric system operations	Indirect relation from consumption results
Impacts assessment	Household and system cost estimates rely on technology projections presented in this report.

This report provides projected cost and performance assumptions for electric technologies considered in the EFS. The study scope includes direct electric technologies that could meet future end-use service demands in all major economic sectors—transportation, residential and commercial buildings, and industry—for the contiguous United States through 2050. The report characterizes the technology projections that will be used in future EFS scenario analysis reports to provide cost, energy use, electricity use, and electric load profiles. The technology data reported here do not reflect predictions; instead, they are designed to cover a wide but plausible range of cost and performance improvements given the significant uncertainties in technology advancement over multiple decades. In addition to providing the foundational data for the EFS analysis, the report is intended to be of interest to other analysts and researchers who wish to assess electrification and electric technologies.

More information, the supporting data associated with this report, links to other reports in the EFS series, and information about the broader study are available at www.nrel.gov/EFS.

Acknowledgments

The Electrification Futures Study (EFS) is led by researchers at the National Renewable Energy Laboratory (NREL) but relies on significant contributions from a large collaboration of researchers from the U.S. Department of Energy (DOE), Evolved Energy Research, Electric Power Research Institute, Lawrence Berkeley National Laboratory, Northern Arizona University, and Oak Ridge National Laboratory. We would like to thank all contributors for useful analysis, data, and input throughout the project.

A technical review committee of senior-level experts provided invaluable input to the overall study, with some committee members sharing thoughtful comments to this specific report as noted below. Although the committee members offered input throughout the study, the results and findings from this analysis and the broader EFS do not necessarily reflect their opinions or the opinions of their institutions. The technical review committee is comprised of the following individuals:

Doug Arent (committee chair)
Joint Institute for Strategic Energy Analysis

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DOE

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Clean Air Task Force

Steve Clemmer
Union of Concerned Scientists

Laura Cozzi
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Joan Ogden
University of California Davis

Laurie ten Hope
California Energy Commission

Susan F. Tierney
Analysis Group, Inc.

This analysis benefited greatly from thoughtful comments and suggestions from several colleagues who generously reviewed either the entire report or portions of it in draft form, including:

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Nomenclature or List of Acronyms

AC	air conditioner
ADOPT	Automotive Deployment Options Projection Tool
AEO	Annual Energy Outlook
AHRI	Air Conditioning, Heating, and Refrigeration Institute
ANL	Argonne National Laboratory
ARC	Assessment Recommendation Code
ASHP	air-source heat pump
BEV	battery electric vehicle
BTO	Buildings Technology Office (DOE)
CARB	California Air Resources Board
CBECS	Commercial Buildings Energy Consumption Survey
ccASHP	cold climate air-source heat pump
CD	charge depleting
CNG	compressed natural gas
COP	coefficient of performance
CS	charge sustaining
DCFC	direct current fast charger
DOE	U.S. Department of Energy
EFS	Electrification Futures Study
EERE	Office of Energy Efficiency and Renewable Energy (DOE)
EIA	U.S. Energy Information Administration (DOE)
EVSE	electric vehicle supply equipment
gge	gallon gasoline equivalent
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle
HPWH	heat pump water heater
HSPF	heat season performance factor
HVAC	heating, ventilation, and air conditioning
IAC	Industrial Assessment Center
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IECC	International Energy Conservation Code
kBtu	thousand British thermal units
kWh	kilowatt-hour
LCOD	levelized cost of driving
LCOS	levelized cost of service
LDV	light-duty vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MDV	medium-duty vehicle
MMBtu	million British thermal units
MMT	million metric tons
MPGe	miles per gallon gasoline equivalent
MSRP	manufacturer’s suggested retail price
NEEP	Northeast Energy Efficiency Partnerships

NEMS	National Energy Modeling System
NEVA	National Economic Value Assessment of Plug-In Electric Vehicles
NG	natural gas
NREL	National Renewable Energy Laboratory
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PPI	Producer Price Index
Quad	quadrillion British thermal units
RECS	Residential Energy Consumption Survey
SCOP	seasonal coefficient of performance
TPC	technical possibility curve
TSD	technical support document
VTO	Vehicle Technologies Office (DOE)
Wh	watt-hour

Abstract

This report provides projected cost and performance assumptions for electric technologies considered in the Electrification Futures Study, a detailed and comprehensive analysis of the effects of widespread electrification of end-use service demands in all major economic sectors—transportation, residential and commercial buildings, and industry—for the contiguous United States through 2050. Using extensive literature searches and expert assessment, the authors identify slow, moderate, and rapid technology advancement sensitivities on technology cost and performance, and they offer a comparative analysis of levelized cost metrics as a reference indicator of total costs. The identification and characterization of these end-use service demand technologies is fundamental to the Electrification Futures Study. This report, the larger Electrification Futures Study, and the associated data and methodologies may be useful to planners and analysts in evaluating the potential role of electrification in an uncertain future. The report could be broadly applicable for other analysts and researchers who wish to assess electrification and electric technologies.

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1 Introduction

The Electrification Futures Study (EFS)[1] is a multi-year research effort designed to explore the future energy and electricity systems in the United States. The EFS uses scenario analysis to prospectively assess electricity consumption—including potential growth, analysis of hourly load profiles for an extensive set of end uses, power sector infrastructure development, electric system operations, and the potential environmental and economy-wide effects of widespread electrification. This report—the first in a series of EFS publications—provides projected cost and performance assumptions for electric technologies as a foundation for future reports in the EFS series. The technology projections characterized in this report will be used in future EFS scenario analysis reports to calculate cost, energy use, electricity use, and electric load profiles. The report is also intended to be of interest to analysts and researchers who wish to assess electrification and electric technologies. Here, we introduce the status of energy and electricity use (Figure 1, page 6), the rationale for the technological scope of this report, the sources used, applications of this analysis within the EFS, and the prospects for electrification in each of the economic sectors.

This report presents foundational data related to projected cost and performance of electric technologies that will be used in the EFS scenario analysis. Because the EFS focuses on power sector analysis, the report emphasizes technologies that have potential for substantial, direct changes to electric demand quantity and timing. The study scope includes direct electric technologies that could meet future end-use service demands in all major economic sectors—transportation, residential and commercial buildings, and industry—for the contiguous United States through 2050. Electrification in this context means replacing technologies that do not use electricity with ones that do—for example, substituting electric vehicles for gasoline or diesel-powered vehicles, electric-powered heat pumps for natural gas furnaces, or electric resistance heating for other sources of process heat. We focus on subsectors and end uses with the most significant historical energy demands, where electrification might be most cost-effective. We do include certain rapidly growing niches, such as battery electric buses, despite their small historical energy demand. We present projections for technologies that are applicable to the end uses and subsectors of most interest for assessing electrification opportunities and for the EFS. The substitute electric technologies considered in this analysis are shown in Table 1.

Table 1. Substitute Electric Technologies Considered in this Analysis[a]

Transportation Sector	Buildings Sector	Industrial Sector
Light-duty cars and trucks (battery and plug-in hybrid electric vehicles) Medium-duty battery electric trucks Heavy-duty battery electric trucks Battery electric buses	Air-source heat pumps Heat pump water heaters	Air-source heat pumps Electric machine drives Industrial heat pumps Electric boilers Electric process heating

[a] Table 1 does not include other potentially important electrification technologies, such as ground-source (or geothermal) heat pumps, fuel cell electric vehicles, and medium- and heavy- duty plug-in hybrid electric vehicles, for reasons that are described in the appropriate sections of this report.

[1] For more information see, www.nrel.gov/EFS.

Although the EFS considers the full U.S. energy system, the present analysis does not assess electrification for all subsectors and end uses. The technological scope is limited in extent, level of detail, and types of metrics examined. Data limitations also constrain the scope. We consider electrification of existing end uses (i.e., switching from current fuels to electricity) but not deeply transformative technological changes or novel or emerging energy services that could alter fundamental aspects of historical demands.[2] The non-electric reference technologies that are assumed to be replaced receive less review and no sensitivity analysis in the report. Our focus throughout is on direct, not indirect, electrification technologies; cost and performance projections are not developed for potential substitutes that do not directly use grid electricity. For example, we do not include electrolysis for hydrogen production or hydrogen fuel cell electric vehicles. This focus represents a scoping decision: it is not intended to be a prediction. It does *not* reflect an assessment of the probability of success of technologies that use hydrogen.[3] Also, we do not subdivide categories of technologies to a more granular level because of data challenges and the study's emphasis on the power sector implications of demand effects of electrification, rather than on detailed market analysis in each subsector. The report does not address other metrics, such as effects of electrification on the electrical grid or potential costs or benefits of electrification. Future EFS reports are planned to cover a subset of these and other topics related to electrification.

In this report we review the data from the literature and consolidate these data into cost and performance sensitivity cases. The report describes the sources of data, calculations, and methods used to develop these assumptions for the EFS series. Sources include published literature, expert judgment, and extrapolation or interpolation. The extent and quality of data vary by sector, and the industrial sector lacks published data for comprehensive analysis.

The projected technology costs presented here will be used in the scenario analysis to be conducted for the EFS that includes multiple technology adoption scenarios. The costs of each adoption scenario will be estimated based on the projections developed in this analysis. Although these technology cost sensitivity cases are used to estimate these relative *scenario costs*, the technology cost and performance highlighted in this report do not dictate the *adoption levels* considered in the technology adoption scenarios. Adoption levels and associated issues will be considered in subsequent EFS reports—not in this report.[4]

Because of the inherent uncertainties in future technology advancement, the EFS relies on a range of technology advancement possibilities in its analysis. In particular, the EFS uses three technology advancement projections through 2050: "slow," "moderate," and "rapid" technology

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[2] Such advances include telepresence and autonomous vehicles that change personal transportation demand, successful development of technologies that target heat to building occupants, or widespread use of additive manufacturing and novel materials displacing current industrial supply chains.
[3] The H2@Scale analysis (DOE 2017e) is exploring the potential for wide-scale hydrogen production and utilization, including hydrogen produced via electrolysis.
[4] The EFS uses the EnergyPATHWAYS energy accounting framework to assess the adoption scenarios. A forthcoming report in the EFS series will document its use in the study.

advancement sensitivity cases that are applied to each adoption scenario (see Table 2).[5] *Documentation of these technology projections is the primary result presented in this report.* The technology data in this report do not reflect predictions; instead, they are designed to cover a wide but plausible range of cost and performance improvements given the significant uncertainties in technology advancement over multiple decades. We do not apply specific probabilities to these technology advancement sensitivities, but the three cases are meant to reflect futures with qualitatively different investment in and improvement of electric technologies cost and performance. For example, the Rapid Advancement projections are consistent with futures in which public and private research and development (R&D) investment in electric technologies spurs technology innovations, manufacturing scale-up increases production efficiencies, and consumer demand and public policy yields technology learning. This projection does not reflect the maximal achievable advancement possibilities—which are impossible to predict—but it does reflect technology cost reductions, performance improvements, or both, relative to currently available options.

Table 2. Combinations of Electrification Adoption Scenarios and Technology Advancement Sensitivity Cases in Future Report on Adoption Scenarios

		Sensitivity Cases (this report)		
		Slow Technology Advancement Sensitivity Case (Slow Advancement)	**Moderate Technology Advancement Sensitivity Case** (Moderate Advancement)	**Rapid Technology Advancement Sensitivity Case** (Rapid Advancement)
Adoption Scenarios (future report)	Reference	Slow Advancement, Reference Adoption	Moderate Advancement, Reference Adoption	Rapid Advancement, Reference Adoption
	Medium	Slow Advancement, Medium Adoption	Moderate Advancement, Medium Adoption	Rapid Advancement, Medium Adoption
	High	Slow Advancement, High Adoption	Moderate Advancement, High Adoption	Rapid Advancement, High Adoption

In contrast, the Slow Advancement cases represent futures where electrification follows current trends without major advances. In many instances, the Slow Advancement cases follow reference projections developed by other organizations, such as the U.S. Energy Information Administration (EIA) in its Annual Energy Outlook (AEO) Reference case (EIA 2017a).

[5] Different rates of technology advancement would impact adoption, but this report does not attempt to quantify this relationship. The EFS scenario analysis (to be presented in future reports) uses the technology advancement sensitivities to estimate electricity consumption and scenario cost benchmarks of the adoption scenarios. For example, the Rapid technology advancement sensitivity does *not* correspond to the high technology adoption, but instead the costs associated with Rapid technology advancement are applied to all technology adoption scenarios to estimate a range of possible costs at each of the levels of technology adoption.

The Moderate Advancement projections fall between the Slow and Rapid projections. The Moderate projections reflect electric technology progress beyond current trends. In other words, the Moderate projections consider additional R&D and technology innovation consistent with futures in which electrification outpaces reference projections. The reference trend corresponds to the Slow Advancement case rather than the Moderate Advancement case because higher electrification levels are of greatest interest to the larger study. A challenge in formulating these projections is the comparability in technology advancement rates across the different end use sectors or across technologies within each sector. The technology advancement rates shown may imply contemporaneous adoption of electrification technologies with divergent costs, or different timing of adoption of technologies with similar costs, where an economic optimization model would assume that low-cost technologies are more fully adopted before high-cost ones. We do not have a more holistic modeling methodology that could generate a quantitative metric to ensure a consistent rate of technology advancement across technologies and sectors. Detailed risk adjusted costs for technology improvement used in an integrated economic model could offer a metric for technology advancement that would be comparable across technologies and sectors, but again, such a model and cost data are not readily available.

Limitations and appropriate applications of this analysis should be considered when these results are used in the EFS series and elsewhere. The long time frame of the study (2050) compounds inherent technological, economic, and market uncertainties, resulting in cost estimates that should be considered speculative. As a result, these costs can appropriately be used as rough initial approximations for types of cost, relative costs among options, and order of magnitude of the costs of end-use electrification, but they are not precise or predictive of actual costs that could emerge in a competitive market. Although the cost and performance projections are not precisely comparable in terms of advancement rate or likelihood, the report does compile data that details variations among the technologies (e.g., by subsector, by end use, and compared with conventional technologies) and by technological components (e.g., fuel, maintenance, installation, and capital equipment). Gaps in these data could inform future research directions.

The EFS considers electrification in all sectors of the U.S. energy system—industry, transportation, and buildings (commercial and residential). A description of the historical U.S. energy system can provide context to electricity's contribution to this broader energy system; across all sectors, U.S. primary energy use totaled 98 quadrillion British thermal units (quads) in 2015 (EIA 2017a).

Figure 1 (page 6) shows how primary energy use from electricity is distributed across all economic sectors and subsectors. Energy use is roughly evenly split between the three economic sectors (industry, transportation, and buildings). Figure 1 also reveals the largest energy users within each sector. For example, in 2015, the light-duty vehicle subsector comprised the majority (57%) of total transportation-related energy use; space and water heating comprised 26% of total buildings-related energy use; and chemical processing and refining comprised 38% of industrial energy use.

Electricity accounts for a large share of the total U.S. energy consumption. In 2015, electricity made up almost 40% (38 quads) of total energy consumption (98 quads).[6] However, electricity consumption is not distributed evenly across sectors. Approximate shares of total final energy consumption from electricity within each sector are 43% for residential buildings,[7] 61% for commercial buildings,[8] 17% for manufacturing (EIA 2017a), and 0.1% for transportation (EIA 2017a). In terms of primary energy (not final energy), Figure 1, Panel A shows how the fraction of primary energy use from electricity differs by sector: industrial (32%), commercial buildings (78%) and residential buildings (70%); and transportation (less than 1%).[9] Within each sector, Panel A also shows the share of energy use from electricity and non-electricity sources across subsectors. Large energy footprints coupled with small electricity footprints are a first-order indication of potential for electrification. The sources of energy and electricity directly and indirectly affect costs, emissions, and other impacts. For example, Figure 1, Panel B shows how 2015 U.S. energy-related direct carbon dioxide emissions (5,259 million metric tons) are distributed among sectors and subsectors.

The remaining sections of this report address each sector in turn. Section 2 describes the transportation sector, including the categories of electric vehicles that we characterize for their projected cost and performance. The scope of end-use services and technologies in the transportation sector includes on-road passenger and freight. Aviation, marine, rail, pipeline, and military transportation services, which accounted for 20% of total transportation primary energy use in 2015 (EIA 2017a), are excluded from consideration in the EFS.[10] For commercial and residential buildings (Section 3), we consider space heating and water heating in the residential and commercial buildings sectors. Other energy uses in the buildings sector are modeled in the EFS, but this report focuses on these electric technologies only. The numerous and diverse industrial sector end uses and technologies are described in Section 4, but data limitations present challenges for the development of industrial sector projections. We summarize our analysis in Section 5. In keeping with our focus on end use, the analysis described in the main body of this report uses a 10% discount rate, which is higher than the 3% or 7% often used as a societal discount rate. Supplemental analyses in Appendix A present sensitivities at 7% and 13% discount rates and offer details on the transportation and buildings sector methods.

[6] This amount includes electricity-related losses. In Figure 1, these losses are allocated to the different sectors and subsectors proportionately to their total electricity consumption.
[7] EIA 2009 Residential Energy Consumption Survey (RECS)
[8] EIA 2012 Commercial Buildings Energy Consumption Survey (CBECS)
[9] Presented in another way, the 38 quads of total 2015 electricity-related energy (including losses) are distributed to the various sectors in the following proportions: 26% for industry, 36% for commercial buildings, 38% for residential buildings, and <0.1% for transportation.
[10] Neither the transportation section (Section 2) nor the industry section (Section 4) separately accounts for industrial transportation services.

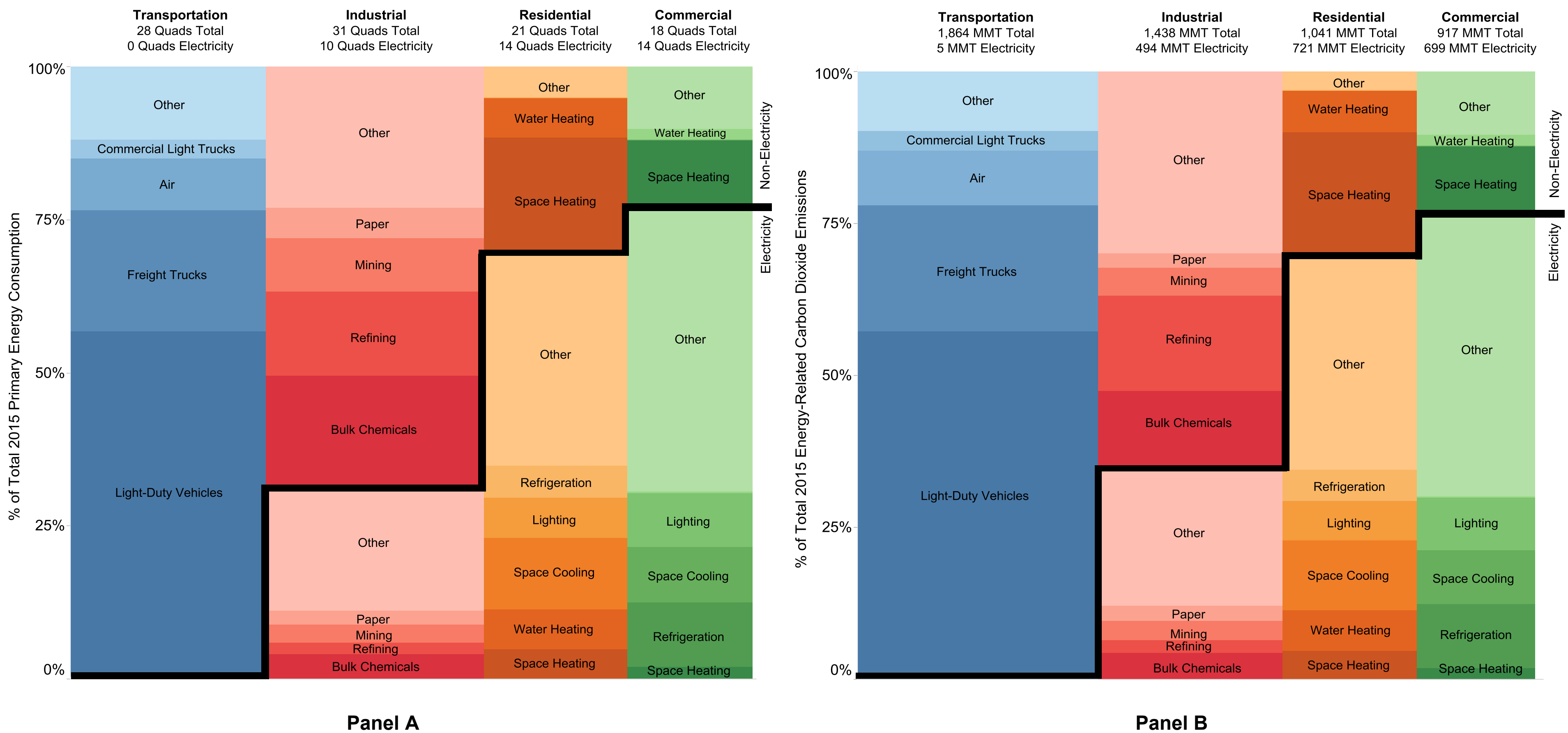

Figure 1. Subsector primary energy consumption and energy-related carbon dioxide emissions shares in 2015 (EIA 2017a)

Total sectoral energy use or emissions appears at the top of each column. Areas of each column are proportional to this number. The bold line separates primary energy used for electricity generation from non-electric energy use. The subsectors with the greatest energy consumption in each “Other” category are as follows:

- Transportation: pipeline, rail, and bus
- Industrial: metal-based durables, construction, and food
- Residential: cooking, televisions, and clothes dryers
- Commercial: office equipment, ventilation, and cooking.

Agriculture energy use (about 1 quad) is not shown because of its relative size.

MMT= million metric tons

2 Transportation

The transportation sector accounts for the third-largest share (28%) of primary energy in the United States (28 quads in 2015), behind the buildings sector (40%) and industrial sector (32%). Transportation is the least-electrified of all sectors: electricity accounts for less than 0.1% of the primary energy used for transportation (EIA 2017a). By far the dominant share of primary energy consumption in transportation consists of petroleum-based liquid fuels for on-road vehicles: motor gasoline and diesel. Biofuels, other petroleum-based liquid fuels, and compressed natural gas or liquefied petroleum gas are also used in the transportation sector, as shown in Table 3.

Table 3. 2015 Energy Consumption (Quads) by Fuel Type and On-Road Transportation Subsector (EIA 2017a)

Subsector	Gasoline[a]	Diesel[a]	CNG/ LNG	E85[a]	Propane	Electricity Consumption	Hydrogen
Light-duty vehicles	15.660	0.062	0.014	0.022	0.008	0.009	0.000
Freight trucks	0.528	4.987	0.032	0.001	0.001	0.000	—
Commercial light trucks	0.591	0.264	0.001	0.002	0.000	—	—
Buses	0.025	0.223	0.016	—	0.000	—	—
Total	**16.805**	**5.535**	**0.063**	**0.024**	**0.009**	**0.009**	**0.000**

[a] Denotes fuels that contain biofuels. Biofuels total about 1.2 quads. Gasoline and diesel consumption includes biofuels. Gasoline is petroleum-based blendstock plus ethanol, which accounted for more than one quad of consumption in 2015 (EIA 2017e). Biodiesel and other renewable fuels accounted for around 0.2 and 0.02 quads of consumption in 2015 respectively (EIA 2017e).

Table 3 does not show air, pipeline fuel, shipping, military, rail, boats, or lubricants, because they are not included in this analysis.

This analysis of the transportation sector includes on-road freight, commercial, and personal transport vehicles. Aviation, marine, rail, pipeline, military transportation services, which accounted for 20% of total transportation primary energy use in 2015 (EIA 2017a), and industrial transportation services are excluded from consideration in this transportation analysis. The size, powertrain type, and duty cycles of the in-scope, on-road vehicles vary, as they are intended to meet diverse service demands. We simplify this complex reality by grouping all vehicles and duty cycles into a limited set of vehicle size categories. Vehicle size categories include light-duty cars, light-duty trucks, medium-duty trucks, heavy-duty trucks, and buses.[11] Powertrain types included in EnergyPATHWAYS—the EFS energy accounting framework[12]—include gasoline internal combustion engine (ICEV), gasoline hybrid electric (HEV), plug-in hybrid electric

[11] In this analysis, medium-duty vehicles are Class 3–6 vehicle types, and heavy-duty vehicles are Class 7–8 trucks. See the Alternative Fuels Data Center (DOE 2017d) for information on vehicle class weights.

[12] A forthcoming report in the EFS series will document the use of the EnergyPATHWAYS framework in the study. Here, we document only the technology cost and performance estimates that will be used as input to the EnergyPATHWAYS framework.

(PHEV), battery electric (BEV), compressed natural gas (CNG), hydrogen fuel cell electric, diesel, diesel hybrid electric, and liquefied natural gas (LNG). For light-duty vehicles, PHEV ranges include 25 and 50 miles, and BEV ranges include 100, 200, and 300 miles. This report covers cost and performance projections for several, but not all, combinations of these powertrain types and vehicle size categories for use in the EnergyPATHWAYS framework, focusing on ICEV, PHEV, and BEV powertrains.

This analysis does not consider hydrogen fuel cell electric vehicles, even though they may be better suited to electrify some transportation applications.[13] The EFS focuses on direct electrification and therefore this report does not assess the cost and performance of other potential alternative transportation technologies (e.g., fuel cell electric vehicles or biofuels).[14] This is strictly a matter of scope, and does not reflect an assessment of relative merits.

The lack of detail in vehicle and duty cycle categories hides opportunities or niches where electrification may be more feasible. For example, both the medium- and heavy-duty truck categories include diverse vocational vehicles with very different requirements and duty cycles that result in a wide range of electrification prospects. Although we do not characterize the ease of electrification and magnitude of each of the vehicles and duty cycles because of data challenges and study scope, freight trucks, especially class 8b, account for the majority of fuel consumption in medium- and heavy-duty trucks (67% according to the National Petroleum Council [2012]). Future studies could extend the scope beyond on-road transportation and refine it to include more granular representation of vehicles and duty cycles.

Historically observed technology cost and performance improvements, especially battery cost reductions, have increased market opportunities for transportation electrification. For example, Nykvist and Nilsson (2015) review the literature and compare numerous cost reduction trajectories for electric vehicle batteries in recent years, and Bloomberg New Energy Finance reports that batteries prices dropped from $1000/kWh in 2010 to $273/kWh in 2016 (Curry 2017), a 73% decrease. The decrease in battery prices directly affects electric vehicle prices: Bloomberg New Energy Finance (Curry 2017) estimate that battery packs generally make up 48% of BEV retail prices, and results from Moawad et al. (2016) show that batteries account for 13%–23% and 34%–61% of model-year 2015 PHEV and BEV retail prices, respectively. Section 2.1 summarizes the literature, and the selected assumptions for battery costs, vehicle cost and performance by vehicle category, maintenance, and infrastructure costs.

In part as a result of battery cost reductions, sales (Figure 2) and model offerings of plug-in electric vehicles (PEVs, including both PHEVs and BEVs), have grown in the U.S. market in recent years. Beyond battery cost reductions, future electric vehicle costs could also decline because of power electronics cost reductions, technology learning-by-doing, and economies of scale along the manufacturing supply chain, many of which are based on global markets for vehicles and their components. A decline in future electric vehicle costs relative to the

[13] The H2@Scale analysis (DOE 2017e) is exploring the potential for wide-scale hydrogen production and utilization, including hydrogen produced via electrolysis.
[14] The *Transportation Energy Futures Study* (M. W. Melaina et al. 2013; Ruth et al. 2013; T. Stephens 2013; Plotkin, Stephens, and McManus 2013), National Research Council (2013), and Heywood and MacKenzie (2015) all analyze the transition to alternative transportation technologies.

conventional vehicles could make PEVs more attractive, contributing to growth in sales. However, this exploration of projections for lower battery costs should not be considered predictive of PEV growth. Section 2.2 discusses the levelized cost of driving and includes important caveats about the potential for misinterpreting cost and performance assumptions as indicators of adoption potential.

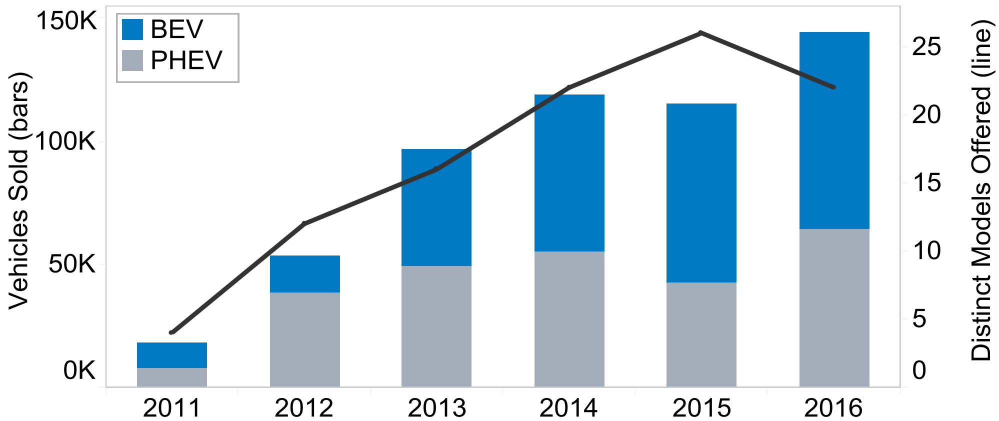

Figure 2. 2011-2016 U.S. PEV sales and distinct models offered. Data from the Alternative Fuels Data Center (DOE 2017h)

The bars represent vehicles sales, and the line represents the number of distinct vehicle models sold.

2.1 Transportation Technology Cost and Performance Sensitivities

The projections in this cost analysis of the transportation sector focus on PEVs. Although the EFS modeling framework represents on-road technologies for each drivetrain as described in the previous section, the projected technology cost and performance assumptions described in this report focus on PEVs only.[15] Specifically, we develop estimates for data elements and transportation technologies listed in Table 4. Medium-duty trucks, heavy-duty trucks, and electric buses encompass various potential sizes, configurations, and charging systems. We do not develop estimates for each of the various vehicle types in these categories because of limited scope, uncertainty, limited data, and, in some cases, small potential market size. Instead, we base different sensitivity cases on different battery sizes and electric ranges of medium-duty and heavy-duty trucks. For example, in the Rapid Advancement case, we assume that trucks can be electrified with smaller batteries, in effect assuming easily electrified market segments or duty cycles are common, or a large charging network is developed; in the Slow Advancement case, we assume that larger batteries are needed, as they would be in the less favorable market segments or duty cycles and for less developed recharging networks.

[15] Fuel cell electric vehicles powered with electrolytic hydrogen could serve many medium- and heavy-duty vehicle market segments, but the EFS scope does not include indirect electrification.

Table 4. Transportation Technologies and Cost Elements Developed in this Report

Transportation Technology	Data Elements for All Technologies
Light-duty cars and trucks	Capital cost
PHEV 25	Fuel efficiency
PHEV 50	Maintenance cost
BEV 100	Infrastructure cost (e.g., electric vehicle supply equipment)
BEV 200	
BEV 300	
Medium-duty battery electric trucks[a]	
Heavy-duty battery electric trucks[b]	
Battery electric buses[c]	

Definitions of light-duty cars and trucks are in text below. The electric ranges of medium- and heavy-duty vehicles and buses are chosen to represent a variety of potential applications and duty-cycles.

[a] Medium-duty battery electric trucks are assumed to have a 50–200 mile range and a 47–187 kWh battery pack.

[b] Heavy-duty battery electric trucks are assumed to have a 92–500 mile range and a 188–1,022 kWh battery pack.

[c] Battery electric buses are assumed to have a 68–426 mile range and a 94–660 kWh battery pack.

In this report, vehicle capital cost refers to expected equilibrium retail price of the vehicle, and it does not include any additional costs that may be required for electric vehicles; estimated infrastructure costs are presented separately from vehicle capital costs, and taxes, registration fees, and manufacturers' incentives are not considered. The assumptions used for these technologies are described in the remainder of this section.

We also develop one set of cost and performance projections for conventional ICEVs for each subsector to be used in the EnergyPATHWAYS framework. [16] The conventional technology estimates are provided in this report for documentation and context. These estimates will be used in other EFS reports to assess the costs of switching to electric technologies. Table 5 shows the references used for the ICEV estimates.

[16] A forthcoming report in the EFS series will document the use of the EnergyPATHWAYS framework in the study. Here, we document only the technology cost and performance estimates that will be used as input to the EnergyPATHWAYS framework.

Table 5. References Used for the Cost and Performances Estimates of Conventional Vehicles

Subsector	Capital Cost	Fuel Economy	Maintenance Cost
Light-duty cars	Moawad et al. (2016)	Moawad et al. (2016)	Al-Alawi and Bradley (2013)
Light-duty trucks	Moawad et al. (2016)	Moawad et al. (2016)	Al-Alawi and Bradley (2013)
Medium-duty vehicles	CARB (2017c)	EIA (2017a)	CARB (2015)
Heavy-duty vehicles	CARB (2017c)	EIA (2017a)	CARB (2015)
Buses	CARB (2017a)	CARB (2017b)	CARB (2017b)

2.1.1 Transportation Literature Review

To develop the transportation technology projections, we perform a literature search targeted on costs and fuel efficiencies of plug-in hybrid and battery electric light-duty vehicles (LDV), including cars and trucks, and battery electric medium-duty vehicles (MDV) and heavy-duty vehicles (HDV), and buses. The literature search specifically focuses on sources that included projections for cost and performance metrics. We identify key sources from the initial set of literature and filled gaps based on targeted searches and consultation with transportation analysts from DOE and national laboratories. This expert consultation supplements the sparse literature on metrics such as maintenance and charging infrastructure costs. A limitation of this literature review is that consultation with the trucking industry was beyond our scope. Where neither literature nor expert assessment provides sufficient data, we develop our own speculative assumptions, and we highlight where further research is needed.

Recent literature includes multiple sources of cost and performance data on electrified LDVs. Our primary source for LDVs is Argonne National Laboratory (ANL) (Moawad et al. 2016), which reports on a variety of technology and cost projections to 2050 based on results from Autonomie (Argonne National Laboratory 2011) model simulations of vehicle powertrain configurations. The vehicle component assumptions for Autonomie used by Moawad et al. (2016) were developed with the collaboration of DOE experts, national laboratories, industry, and academia. Many of the other sources in the literature refer to ANL/Moawad or to EIA projections of LDV costs and fuel economy through 2050 that are part of the AEO using the National Energy Modeling System (NEMS). Still other sources rely on expert opinions.

Although current electrification cost and performance in other transportation subsectors (MDV, HDV, and buses) are reported in the literature, no source for projections through 2050 that is comparable to the sources for LDVs is identified. The key sources for these subsectors were documents provided by the California Air Resources Board (CARB) Innovative Clean Transit workgroup (CARB 2017a) and manufacturer specifications for current models from manufacturers BYD and Proterra (BYD 2017; Proterra 2017). A European study conducted by CE Delft (den Boer et al. 2013) includes projected costs for high-level components (e.g., battery, motor, and additional electronic systems) and the resulting total vehicle costs for battery electric MDVs and HDVs through 2030, but these may not be representative of vehicle configurations and markets in the United States. CARB (2016) presents a literature review of battery costs for electric HDVs, but we did not find long-term projections to 2050 for heavy-duty specific battery costs in our literature search. Electrification of transportation is rapidly changing, and the literature does not necessarily reflect recent developments. The literature search reveals a gap in sources for projected cost and performance of electrification beyond the light-duty subsector.

2.1.2 Battery Costs

Battery costs apply to all vehicle types. The projected battery cost assumptions for BEVs used in this analysis, and the references for each estimate, are shown in Figure 3. Costs have decreased rapidly in recent years, falling 19% per year on average from 2010 to 2015, according to Curry (2017). If this trend continued, costs would reach unexpectedly low values, so we assume slower cost reductions through 2050. The Slow, Moderate, and Rapid Advancement cases decrease by 4%, 2%, and 1%, per year on average respectively. The values for current battery costs were adjusted downward from the estimates in Moawad et al. (2016), to reflect today's value provided by Bloomberg New Energy Finance of $273/kWh in 2016 (Curry 2017). The long-term estimates in the Slow and Moderate cases are taken from Moawad et al. (2016). To update the Rapid Advancement case, we adjusted the values to align with DOE Vehicle Technologies Office (DOE-VTO) goals of $100/kWh in the near term (Islam et al. forthcoming) and an ultimate goal of $80/kWh in the long term (Howell 2017). Based on discussions with the DOE-VTO, we assume the $100/kWh target to be met in 2033, and the $80/kWh target to be met in 2038, after which the costs remain constant at $80/kWh. Further cost reductions are likely possible, but assessing the ultimate technology endpoint is difficult given future uncertainty. The actual timing of cost declines will depend on R&D investment.

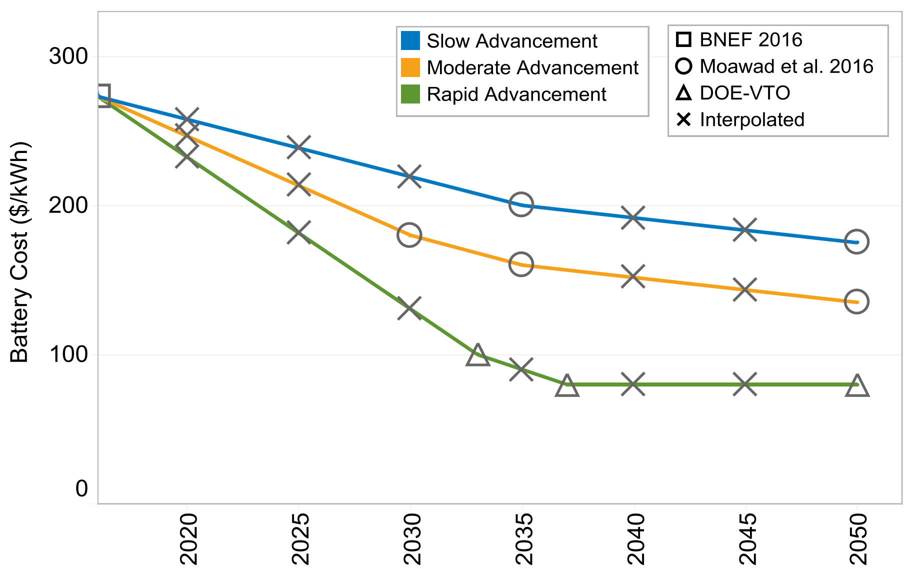

Figure 3. Projected battery cost assumptions for BEVs

The 2016 cost is from Bloomberg New Energy Finance (Curry 2017) ; Slow and Moderate Advancement costs are based on Moawad et al. (2016); Rapid Advancement costs are based on DOE-VTO goals (Islam et al. forthcoming; Howell 2017).

2.1.3 Light-Duty Vehicles

Light-duty cars and trucks—which make up the largest portion of the on-road vehicle fleet, transportation-related energy use, emissions, and vehicle miles traveled—have been the primary focus of transportation electrification to date. While PEVs accounted for less than 1% of all LDV sales in 2015,[17] Figure 2 shows that PEV sales and model offerings generally increased from 2011 to 2016. Recent literature projects a decreasing capital cost difference between PEVs and conventional vehicles, primarily because of the rapidly decreasing costs of batteries (EIA 2017a; Moawad et al. 2016; Heywood and MacKenzie 2015).

As described in Section 1, for all in-scope electric technologies, we develop three distinct technology advancement sensitivity cases—Slow Advancement, Moderate Advancement, and Rapid Advancement —to reflect a range of optimism of future innovation. To develop these three cost projections for LDVs, we primarily rely on estimates from ANL developed using the Autonomie model for the vehicle capital costs and efficiencies (Moawad et al. 2016). The ANL analysis supports the DOE Vehicle Technologies Office and the DOE Fuel Cell Technologies Office by assessing the impacts of LDV research as part of the Government Performance and Results Act analysis (Stephens et al. 2016). We choose the ANL analysis from Moawad et al. (2016) as our primary source because it is a major DOE analysis that includes cost and technology projections and sensitivities. It includes "low risk" level estimates based on regulation-driven original-equipment-manufacturer improvements, "high risk" estimates based on DOE-VTO technology goals, as well as an intermediate "average risk" case. We do not directly use these trajectories, but they provide a range of projected cost and performance estimates from which to select sensitivity cases for this cost analysis.

Using the estimates in the ANL analysis, we develop projected technology assumptions for LDVs. The vehicle cost metric is intended to represent long-term marginal cost; some vehicles using new technologies may initially be sold at a loss.[18] The high, average, and low risk ANL estimates were used for the Rapid, Moderate, and Slow projections respectively, with the following modifications. The ANL estimates were adjusted so that costs and fuel efficiencies change monotonically.[19] For this analysis, we use ANL ranges as reported (Moawad et al. 2016), not as adjusted in subsequent reports for real-world driving conditions or battery degradation (Elgowainy, Han, and Ward 2016).[20] We adjust the ANL cost and fuel economy estimates for 10 and 40 mile range vehicles to account for the larger battery sizes required for the 25 and 50 mile PHEV range categories assumed for this analysis,[21] which were selected to reflect recent trends

[17] PEVs accounted for 114 thousand (DOE 2017h) of the 17.4 million total light-duty vehicle sales in 2015 (DOE 2017g).

[18] Examples of reports of vehicles sold at a loss include Bhuiyan (2017), Ferris (2016), and Cole (2014).

[19] The Moawad et al. (2016) analysis relies on Monte Carlo simulations to develop estimates. As a result, some trajectories exhibited slight non-monotonic behavior throughout time. We adjusted the estimates to avoid this behavior (e.g. all fuel economy estimates increase throughout time).

[20] The range of a PHEV represents the miles that can be driven on a single battery charge, without the use of auxiliary fuel. Battery ranges may be reported as beginning of life or end of life, and may reflect test cycle or real-world driving conditions.

[21] The PHEV costs were adjusted according to the formulation provided by Vanek, Albright, and Angenent (2012), and the efficiencies were scaled based on the DOE estimate that a 10% decrease in weight can result in a 6%–8% improvement in fuel economy (DOE 2017f).

toward longer-range vehicles (Slowik, Pavlenko, and Lutsey 2016). We do not adjust the ranges for the 100-, 200-, and 300-mile range BEVs. More significantly, we adjust the BEV vehicle costs based on updated assumptions for current and projected battery costs as described above.[22]

Figure 4 and Figure 5 show the assumed projections for vehicle capital cost for light-duty cars and trucks respectively; Figure 6 and Figure 7 show projections for fuel efficiency. Three projections are shown reflecting the Slow Advancement, Moderate Advancement, and Rapid Advancement projections for use in the EFS. The figures also show data used in EIA (2017a) and the EnergyPATHWAYS inputs for conventional vehicles for context. The ICEV reference vehicle class does not include hybrid electric vehicles. The reference vehicle for all powertrains is a mid-sized sedan for light-duty cars and a pickup for light-duty trucks.[23] The light-duty truck used in EIA (2017a) is a small pickup truck, which is less expensive and has higher fuel economy than the our assumed light-duty truck, which is based on the average pickup.

Cost projections primarily reflect battery technology cost improvement, such that the spread among the technologies is largely a function of battery size, with PHEV 25 vehicles having a smaller spread between Slow Advancement and Rapid Advancement projections than vehicles with larger batteries. Because the larger battery represents most of the incremental cost of the BEV 300, assumed reductions in battery cost lead to rapid reduction in the BEV 300 capital cost. Vehicles with greater electric ranges will have greater reductions in costs over time, assuming battery costs will decrease faster than other component costs. In comparison to the BEV battery estimates from EIA (EIA 2017a; Lynes 2017) , we assume lower battery costs, which contributes to the lower costs estimated for our projections.

[22] We do not adjust the PHEV battery cost assumptions from Moawad et al. (2016), because we did not find data sources to suggest different current costs for PHEV batteries. Also, the battery costs for PHEVs do not affect the capital cost of the vehicle as significantly as for BEVs.
[23] The best-selling mid-sized sedan and pickup are the Toyota Corolla and the Chevrolet Silverado respectively.

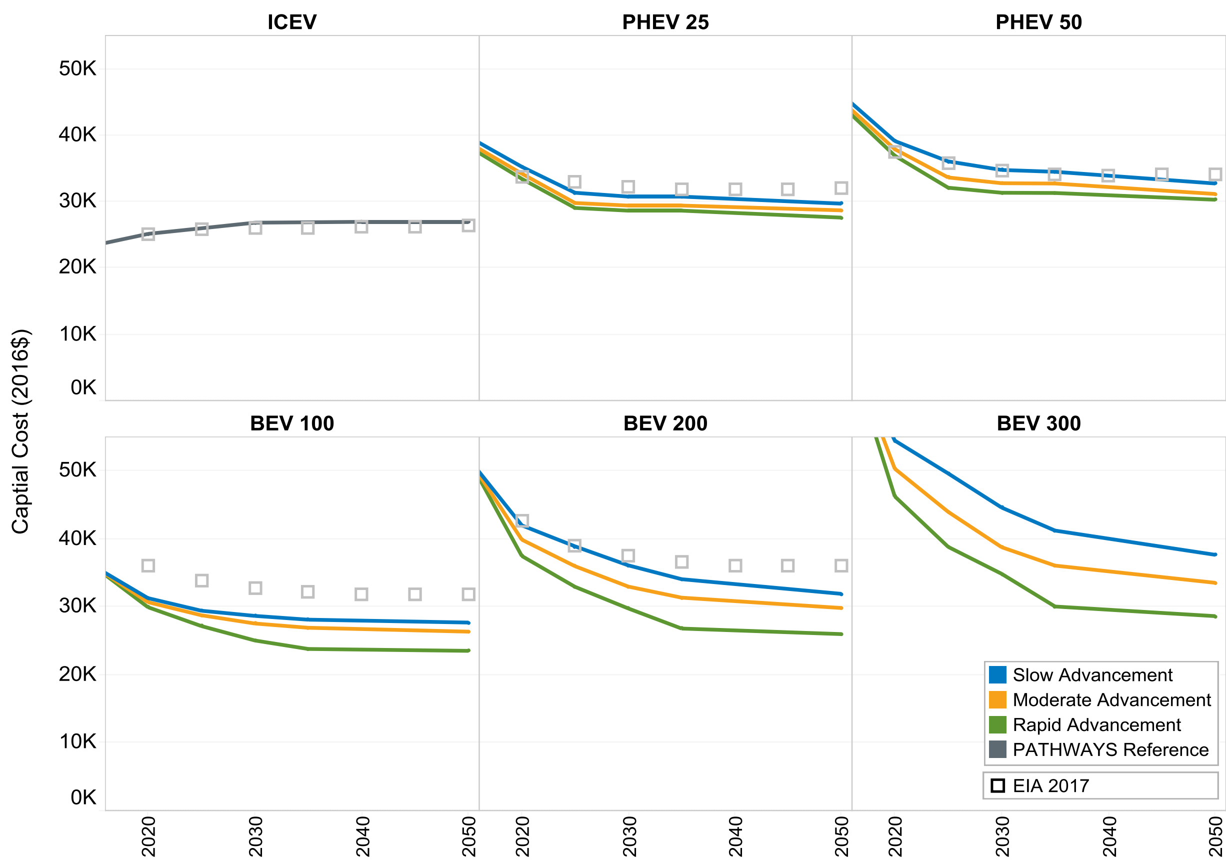

Figure 4. Vehicle-only capital cost projections for light-duty cars

Capital cost represents the expected long-term equilibrium vehicle retail purchase price, and it does not include charging infrastructure costs. The EIA PHEV 25 data points represent a PHEV 10, and the EIA PHEV 50 data points represent a PHEV 40. The capital cost for a BEV 300 car is $71,000 in 2015.

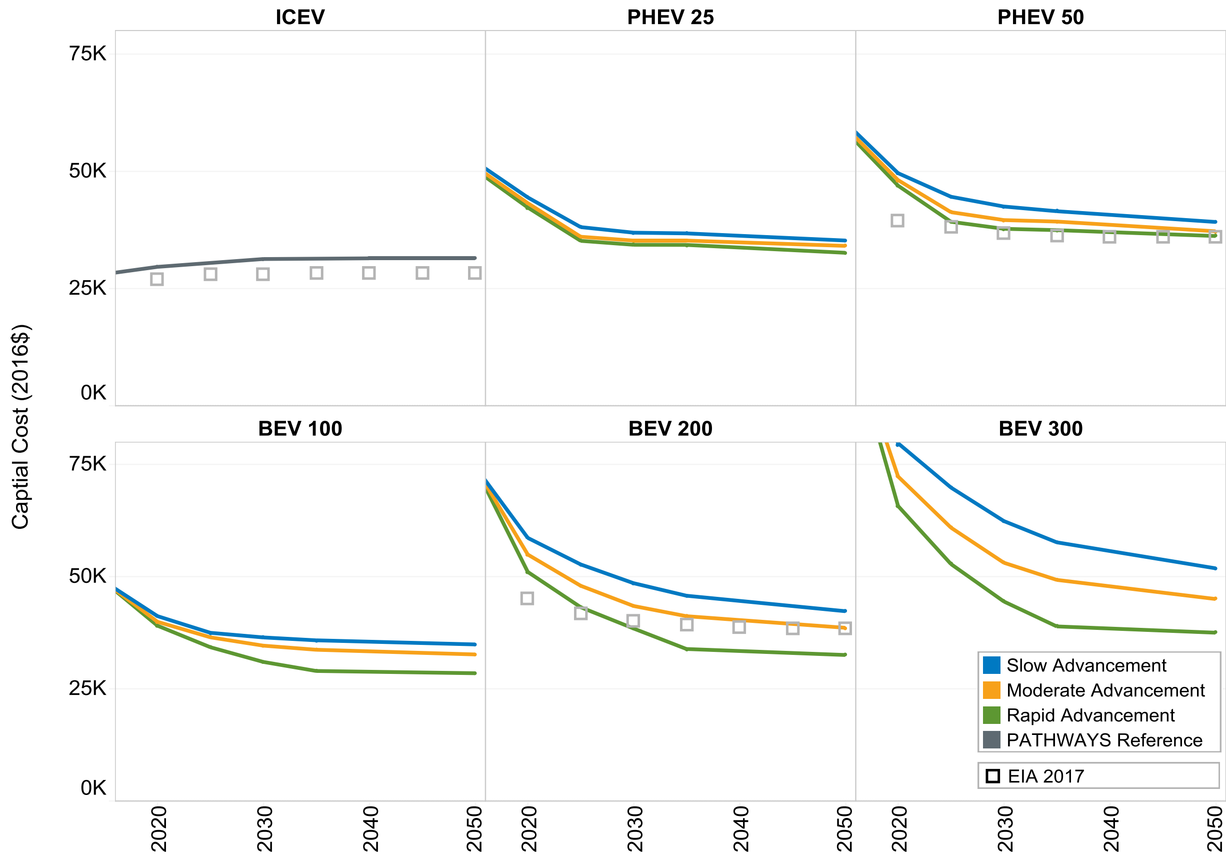

Figure 5. Vehicle-only capital cost projections for light-duty trucks

Capital cost represents the expected long-term equilibrium vehicle retail purchase price, and it does not include charging infrastructure costs. The EIA PHEV 25 data points represent a PHEV 10, and the EIA PHEV 50 data points represent a PHEV 40. The EIA ICEV represents a small pickup truck. The capital cost for a BEV 300 truck is $107,000 in 2015. EIA does not include BEV 200 light-duty trucks until 2020.

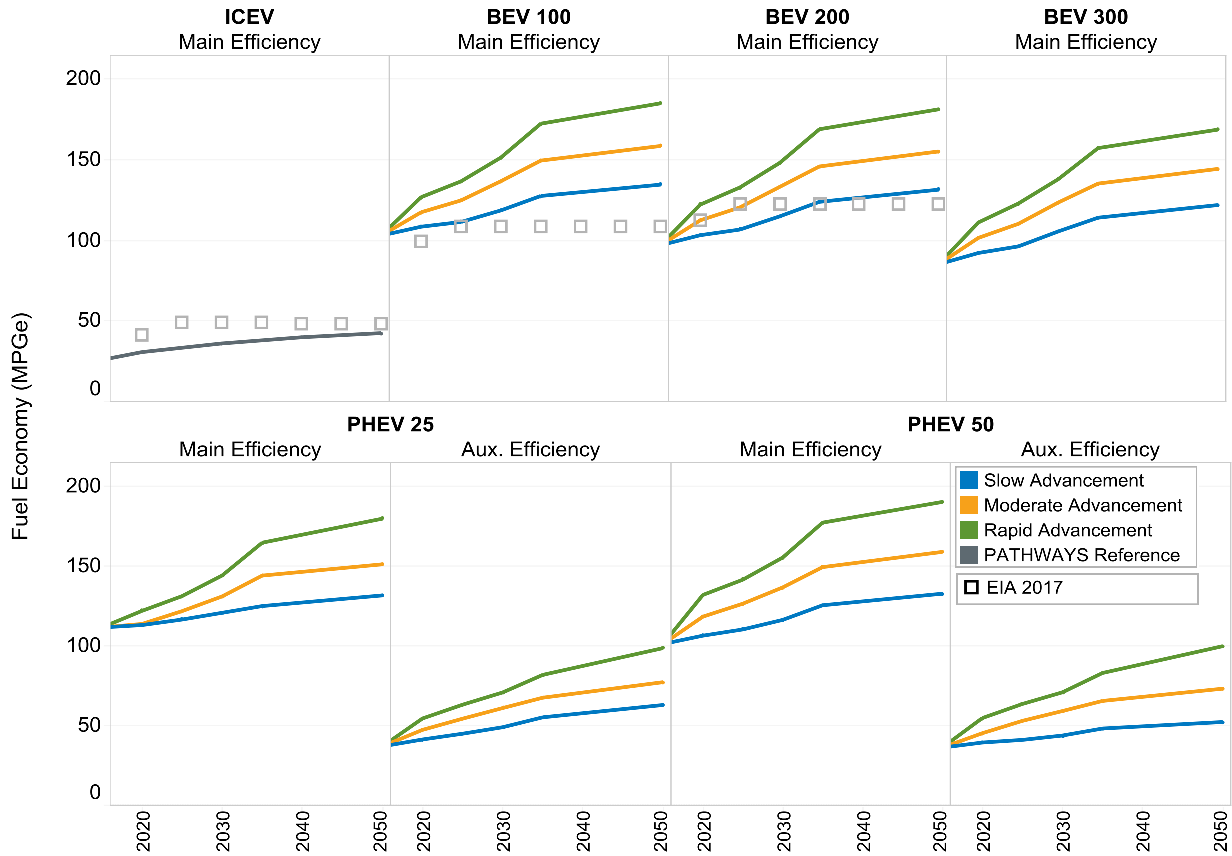

Figure 6. Fuel efficiency projections for light-duty cars

Moawad et al. (2016) presents estimates for 2035 and 2050. The data above shows the linear interpolation between those two points, which causes the kink in fuel economy projections in 2035.

The ICEV category does not include hybrid-electric vehicles.

Moawad et al. (2016) gives higher main efficiencies for PHEV 50 than for PHEV 25, and they are different hybrid configurations.

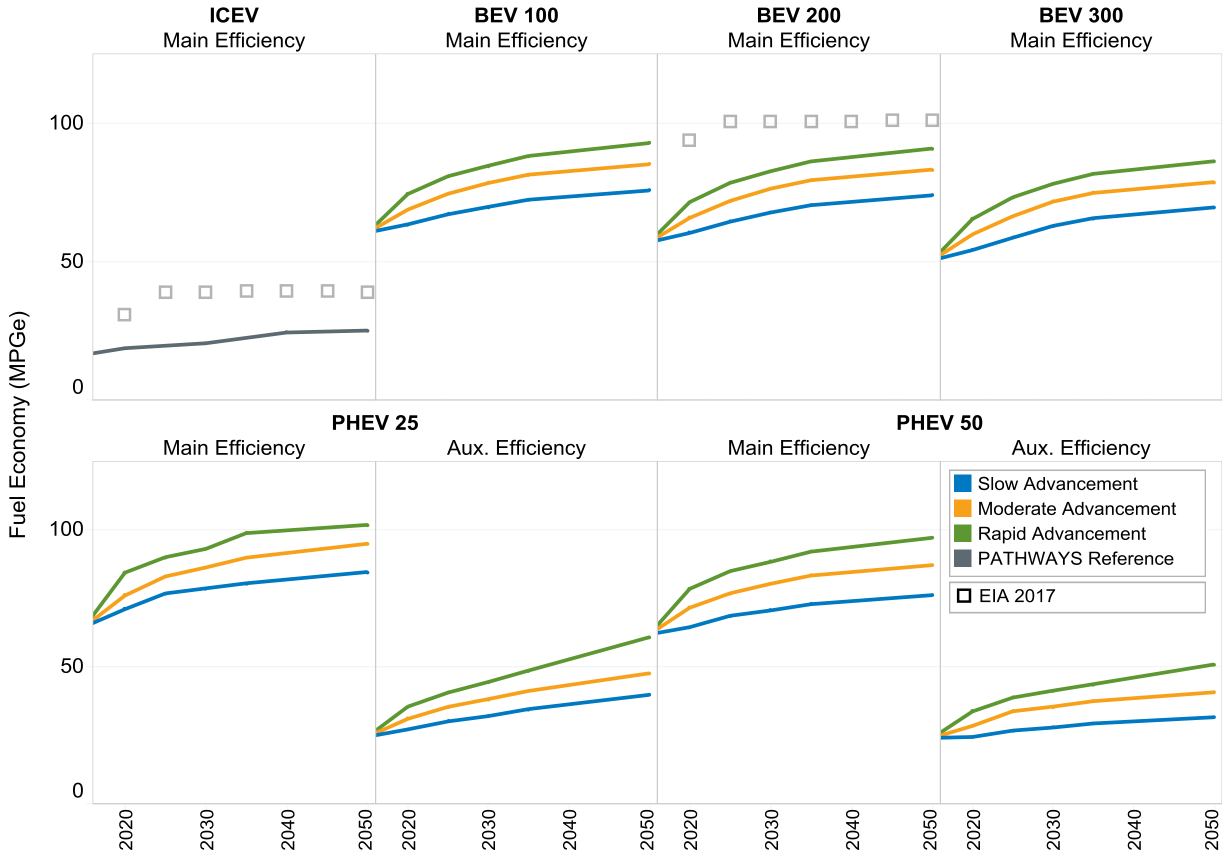

Figure 7. Fuel efficiency projections for light-duty trucks

Moawad et al. (2016) presents estimates for 2035 and 2050. The data above shows the linear interpolation between those two points, which causes the kink in fuel economy projections in 2035.

The ICEV category does not include hybrid-electric vehicles.

Moawad et al. (2016) gives higher main efficiencies for PHEV 50 than for PHEV 25, and they are different hybrid configurations.

Two types of vehicle fuel efficiency are represented in Figure 6 and Figure 7: main efficiency and auxiliary efficiency, and both are shown as miles per gallon of gasoline equivalent (MPGe).[24] We model both efficiency types to be consistent with the EnergyPATHWAYS input structure. The main efficiency represents the fuel efficiency while the vehicle is operating on its primary source of energy (e.g., electricity for BEVs, and gasoline for reference gasoline vehicles). In the case of PHEVs, the main efficiency represents the performance on electricity (charge depleting [CD] mode), and the auxiliary efficiency represents the performance on the liquid fuel (charge sustaining [CS] mode). These definitions are used to align with EnergyPATHWAYS.

The main and auxiliary efficiency projections were based on Moawad et al. (2016), with the adjustments described previously in this section applied.[25] For PHEVs, the utility factor reflects the percentage of miles driven on gasoline and electricity; the limited all-electric range of PHEVs means the electric share of miles will depend on how far the vehicle needs to travel between charging opportunities. For the levelized cost calculations in Section 2.2, we base the utility factors on the calculated values from the National Economic Value Assessment of Plug-In Electric Vehicles (NEVA) study (Melaina et al. 2016), which aims to represent real-world driving behavior.

The differences in fuel efficiency improvement projected by EIA (2017a) versus Moawad et al. (2016) are primarily due to their respective representation of fuel regulations. The NEMS model, used by EIA, reflects the current law of the Corporate Average Fuel Economy program standards (EIA 2017d). The standards are modeled through 2025, and then held constant at 2025 levels through 2050. While the ANL analysis projections are aligned with expected original-equipment-manufacturer improvements and DOE-VTO technology goals, the study does not explicitly incorporate Corporate Average Fuel Economy standards. Another difference compared to EIA is that fuel economy improvements are assumed to continue through 2050.

2.1.4 Medium-Duty and Heavy-Duty Vehicles

For the MDV and HDV subsectors, we develop cost and performance estimates for the battery electric vehicle technologies, without subdividing each of these vehicle types due to limitations of scope and data. Commercially available MDVs and HDVs, and analysis from the CARB Innovative Clean Transit workgroup (CARB 2017a) are the primary references for estimates in these subsectors. We also use AEO 2017 (EIA 2017a) to develop vehicle efficiency projections, and the battery costs presented in Figure 3 to develop cost projections.

The normal operation of MDVs and HDVs poses significant challenges to their widespread electrification based on weight, volume, and range issues. Electrification is anticipated to be more challenging for larger vehicles, because they require larger and more energy-dense batteries (CARB 2015). For freight trucks, the additional weight and volume needed for batteries

[24] Fuel economies were converted from Wh/mi to MPGe using 33,700 Wh per gallon of gasoline (DOE 2017a).
[25]The main efficiency and auxiliary projections were based on the following fields from Moawad et al. (2016): “Adjusted Electricity Consumption, Combined 55/45 - sticker, CD (Wh/mi)” and “Adjusted Fuel Economy, Combined 55/45 - sticker, CS, Fuel (MPGe).” The “55/45” represents the percentage split between city (55%) and highway (45%) driving.

might reduce payload capacity. Moreover, long-haul freight trucks have higher utilization rates than LDVs, leaving less time for charging.[26] Even with these challenges, various battery electric MDV and HDV models are commercially available, and manufacturers continue to announce new products. In 2016, eight commercially available MDV and HDV PEV options were identified by Oak Ridge National Laboratory (Birky et al. 2017). In addition, manufacturers Cummins and Daimler both recently announced battery electric heavy-duty models, and Tesla is slated to show a concept truck in 2017 (Muller 2017; Behrmann 2017; Vartabedian 2017).

Medium-duty trucks, heavy-duty trucks, and electric buses encompass various potential sizes, configurations, and charging systems. We approximate this diversity by basing the different sensitivity cases on different vehicle types, even though the resulting approximation is not strictly aligned with the Slow, Moderate, and Rapid conceptualization of these cases. This means we develop the Slow Advancement case using larger battery sizes, longer electric ranges, and lower reliance on infrastructure than the Rapid Advancement case. Although these cases are grounded quantitatively in these specific estimates, the purpose is to estimate a range of costs, rather than to assert that the specific technologies used for these cost estimates will be adopted. In particular, systems costs, based here on direct current fast charger (DCFC) infrastructure costs, might eventually include dynamic charging (inductive or catenary), battery-swapping, or technologies yet to be discovered. Section 2.1.7 details the costs and other assumptions for charging infrastructure, and Appendix A includes a calculation for catenary charging infrastructure.

In the medium- and heavy-duty subsectors, we consider only BEVs. The EFS does not emphasize indirect electrification technologies (e.g., hydrogen produced from electrolysis), therefore we do not include fuel-cell electric vehicles. This scope simplifies the complex reality of the great diversity of vehicle requirements in the medium- and heavy-duty subsectors, where successful vehicles might include PHEVs, plug-in BEVs, BEVs that use dynamic charging (inductive or catenary), or fuel cell electric vehicles. These solutions entail different vehicle technologies and infrastructure requirements. Excluding these powertrains and charging options is not intended to undervalue the potential for PHEVs and fuel cell electric vehicles.

The MDV and HDV specifications used for this analysis are listed in Table 6. The selected ranges are meant to encompass the variations in duty cycles within these subsectors, with the Rapid Advancement range covering a majority of trips. Birky et al. (2017) show that 60% of heavy-duty sleeper cab trips, and over 95% of heavy-duty day cab trips are less than 500 miles.[27] Therefore, we use 500 miles as the electric range in the Slow Advancement case for HDVs, as it would require less extensive infrastructure requirements. Over 90% of medium- and heavy-duty single unit truck trips are under 200 miles (Birky et al. 2017), which is used as the electric range in Slow Advancement case for MDVs. We base the BEV assumptions for the MDV in the Moderate Advancement case and for the HDV in the Rapid Advancement case on current model

[26] Specific applications of HDVs (e.g., drayage and refuse trucks, and intercity buses) that have shorter ranges, lower speeds, and more frequent stops may have a higher potential for electrification (CARB 2015).
[27] The trip distributions from Birky et al. (2017) are based on 2002 data from the Vehicle Inventory and Use Survey, which are the most recent data available.

offerings from vehicle manufacturer BYD,[28] reflecting the idea that the current MDV market may be slightly more mature than the current HDV market. The large battery size assumed in the HDV Slow Advancement case would add significant weight to the vehicle, limiting payload capacity,[29] and advances in battery energy density would need to occur for this technology to be more competitive.

Table 6. MDV and HDV Range and Battery Size by Technology Advancement Sensitivity

Subsector	Vehicle Specification	Slow Advancement	Moderate Advancement	Rapid Advancement
MDV	Electric Range (mi)	200	155[a]	50
	Battery size (kWh)	187	145[a]	47
HDV	Electric range (mi)	500	200	92[b]
	Battery size (kWh)	1,022	409	188[b]

[a] Specifications are based on class-5 T5 model from BYD (2017).

[b] Specifications are based on class-8 T9 model from BYD (2017).

The assumed capital cost projections for MDVs and HDVs are shown in Figure 8 and Figure 9 respectively. The capital cost estimates for the actual vehicle models are reported by the New York State Truck Voucher Incentive Program (New York State 2017). We scale these costs according to battery size for the other cases, based on our 2016 battery cost estimate of $273/kWh (Curry 2017). The projected costs shown are calculated using the battery cost trajectories described in Section 2.1.2 (Figure 3); however, the battery costs are scaled by a factor of 1.5 to account for higher-cost batteries for MDVs and HDVs compared to LDVs.[30] Figure 8 and Figure 9 show the cost trajectories for each vehicle range and battery cost trajectory, but we consider only the Moderate battery cost advancement trajectories for our Slow, Moderate, and Rapid Advancement cases. Vehicles with larger batteries have faster cost decreases, because a greater proportion of the capital cost is attributed to batteries. The Rapid Advancement cases for MDVs and HDVs approach, but do not fall below, the reference vehicle cost.

[28] The current BYD model with a 92-mile range is used for the HDV Slow Advancement case to reflect trends toward longer-range vehicles suggested by recent product announcements from other manufacturers; the models announced by Cummins, Daimler, and Tesla are stated to have battery ranges up to 300 (for the extended range version), 220, and 300 miles respectively (Muller 2017; Behrmann 2017; Vartabedian 2017).

[29] A 1,022 kWh battery with an energy density of 150 Wh/kg (CARB 2016) would weigh close to 15,000 lbs. This would displace 25% of the 54,000 lb. maximum payload capacity (Transportation Research Board and National Research Council 2010) of a class 8 b truck .

[30] According to CARB (2016), battery costs for HDVs are currently higher than for LDVs because of differences in packaging and thermal management systems, and lower production volumes. We base our scale up factor of 1.5 on heavy-duty battery cost estimates from CARB (2017b) of $565/kWh in 2018 and $348/kWh in 2023, which are respectively 1.9 and 1.5 times greater than the interpolated estimates in the Moawad et al. (2016) moderate cost trajectory. We selected 1.5 from this range to reflect assumptions on battery technology advancement. These approximations were necessary because of limited literature on HDV-specific battery cost projections.

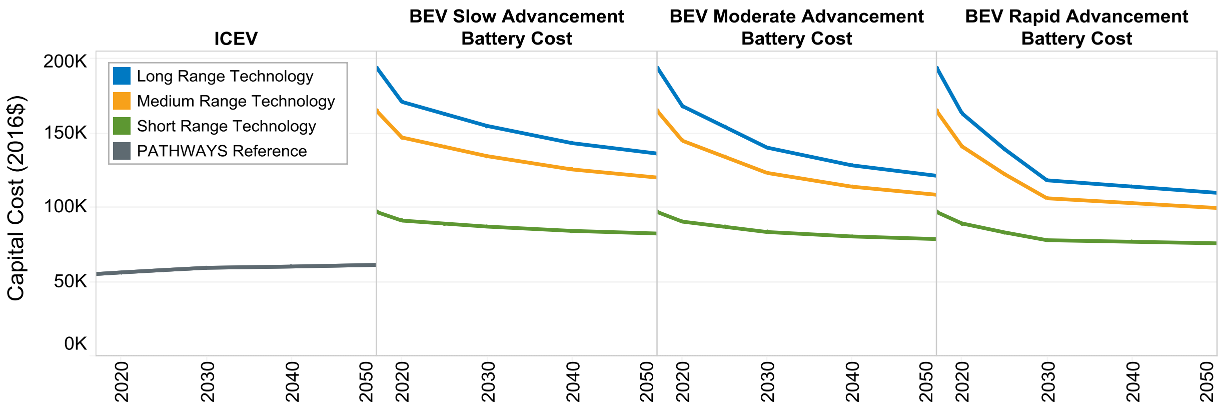

Figure 8. Vehicle-only capital cost projections for MDVs

The BEV Moderate Battery Cost Advancement trajectories are used for the EFS Slow, Moderate, and Rapid Advancement cases.

Capital cost represents the expected long-term equilibrium vehicle retail purchase price, and it does not include charging infrastructure costs.

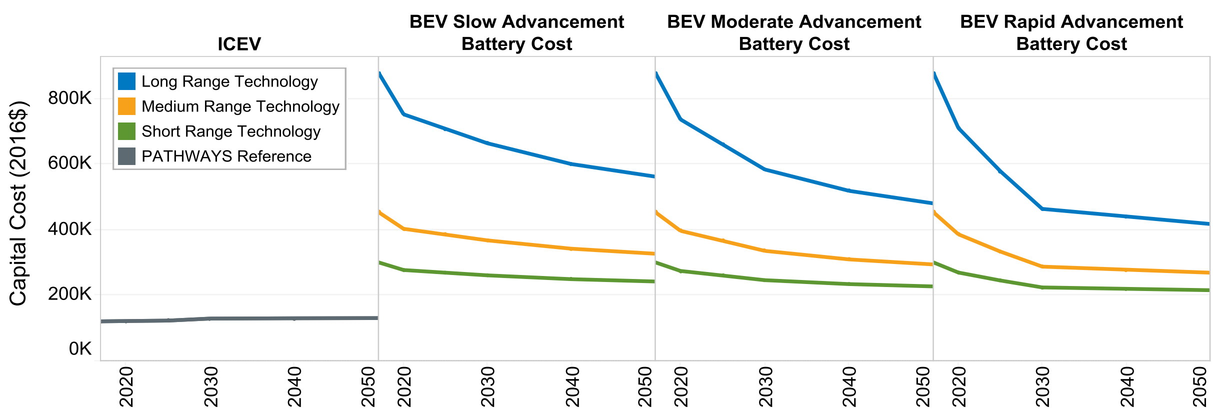

Figure 9. Vehicle-only capital cost projections for HDVs

The BEV Moderate Advancement Battery Cost trajectories are used for the EFS Slow, Moderate, and Rapid Advancement cases.

Capital cost represents the expected long-term equilibrium vehicle retail purchase price, and it does not include charging infrastructure costs.

Figure 10 shows the fuel efficiency for MDVs and HDVs for the three EFS technology advancement sensitivities. The reference ICEV fuel economies are based on the AEO 2017 Reference case projection (EIA 2017a). EIA incorporates both the Phase I and Phase II greenhouse gas emissions standards for medium- and heavy- duty vehicles from EPA and National Highway Traffic Safety Administration (EIA 2017d). The reference vehicle is meant to be representative of the typical on-road vehicle, and does not reflect the potential for advanced fuel-efficient technologies, such as those promoted in Run On Less ("Run On Less" n.d.). We also base the Moderate Advancement efficiencies for BEVs on the AEO 2017 Reference case projections. Because we have only a single source of published data on the projected fuel efficiency of battery electric MDVs and HDVs, we assume Slow Advancement and Rapid Advancement cases such that they reach a 20% spread in efficiency by 2050.

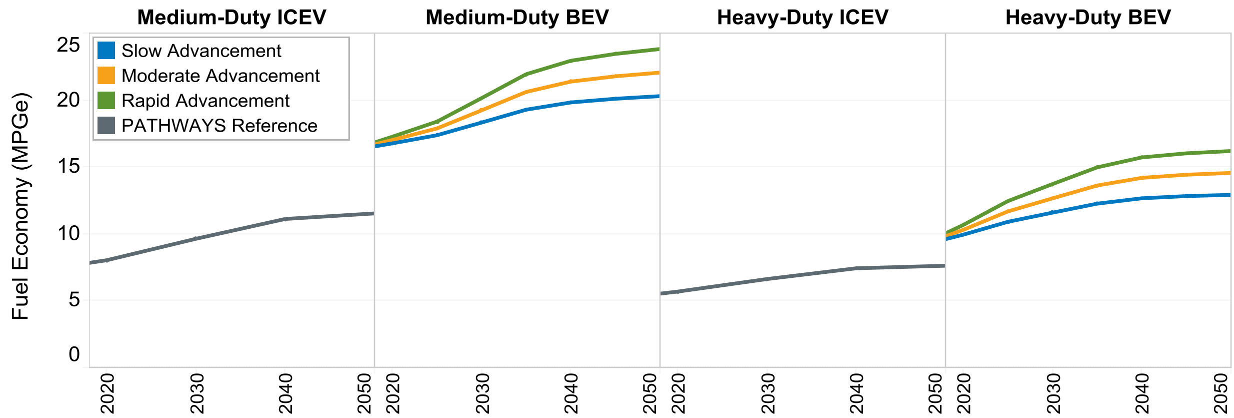

Figure 10. Fuel efficiency projections for MDVs and HDVs

2.1.5 Buses

Battery electric buses account for a small share of the bus market in the United States,[31] and cities have tended to replace diesel buses with natural gas and hybrid electric drivetrains. The global market for electric buses is experiencing growth; China deployed close to 300,000 battery electric buses in 2016 (IEA 2017). Although the deployment of battery electric buses is on the rise, the literature on projected costs and performance of buses is limited, and it is not nearly as developed as for LDVs. We rely on cost estimates for currently available models from the electric bus manufacturer, Proterra, and from analyses from CARB to develop projections for this subsector.

We expect the capital cost trajectory of electric buses to follow similar behavior to that of MDVs and HDVs, because decreasing battery costs will account for the majority of cost reductions. Therefore, we follow a similar approach to that used for MDVs and HDVs (Section 2.1.4). The vehicle specifications used for buses, shown in Table 7, are based on the range of actual available models offered by Proterra (2017).

[31] There were 200 electric buses in the United States in 2016 (International Energy Agency 2017) and about 71,000 total buses in the United States in 2015 (DOE 2016a).

Table 7. Vehicle Specifications for Buses

Vehicle Specification	Slow Advancement[a]	Moderate Advancement[b]	Rapid Advancement[c]
Electric range (mi)	68	238	426
Battery size (kWh)	94	330	660

[a] Specifications are based on FC model from Proterra (Proterra 2017).

[b] Specifications are based on XR+ model from Proterra (Proterra 2017).

[c] Specifications are based on E2 Max model from Proterra (Proterra 2017).

Figure 11 shows the projected capital costs for electric buses. The share of total vehicle cost attributed to batteries is smaller for buses than for the MDVs and HDVs in this analysis because of the cost of additional bus components (e.g., interior seating), so we see a lower percentage reduction in capital costs over time as batteries become cheaper. Similarly to cost reductions for MDVs and HDVs, the absolute cost reduction comes from the assumed decreases in battery costs; therefore, longer-range vehicles decrease in cost more rapidly than shorter range vehicles do. The fuel efficiency inputs for electric buses are also shown in Figure 12. These projections for bus fuel efficiency are based on the values for HDVs. We use CARB (2017b) for current estimated fuel efficiency, and we apply the same incremental change that is observed in the HDVs (developed from AEO 2017).[32]

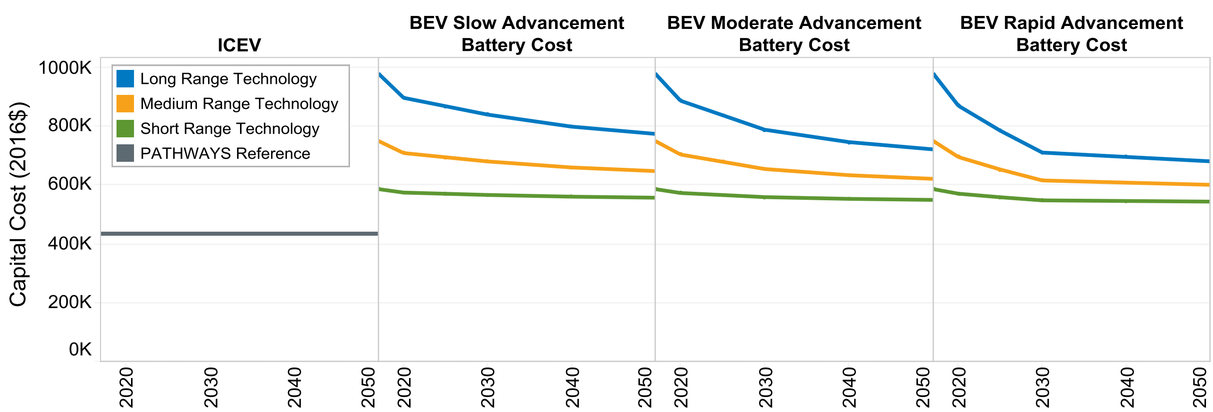

Figure 11. Vehicle-only capital cost projections for buses

The BEV Moderate Battery Cost Advancement trajectories are used for the EFS Slow, Moderate, and Rapid Advancement cases.

Capital cost represents the expected long-term equilibrium vehicle retail purchase price, and it does not include charging infrastructure costs.

[32] Because the EFS analysis required more technology categories in the bus subsector than existed in EnergyPATHWAYS, we developed reference inputs for diesel, hybrid, and CNG buses. Capital costs and maintenance costs are based on CARB (2017b), and efficiencies are based on AEO 2017 reference projections for similar technologies of HDVs

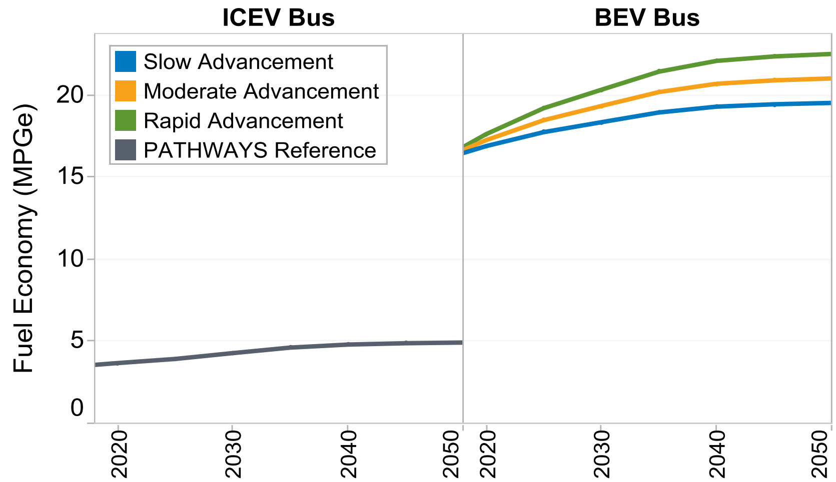

Figure 12. Fuel efficiency projections for buses

2.1.6 Maintenance

BEVs are generally expected to have lower maintenance costs than conventional vehicles because BEVs have fewer moving parts (DOE 2017c). However, maintenance costs remain uncertain (Sonnad 2017; Saxton 2013). This cost difference is expected to increase with deployment of BEVs, as greater deployment leads to more maintenance experience. Although empirical support for these expectations about maintenance costs is limited, we apply these ideas when we select the maintenance costs assumptions to use for PEVs, and we align our assumptions with the limited literature.

The selected assumptions for PEV maintenance costs are compared to those for the corresponding conventional vehicles in Table 8. We assume the same maintenance costs for each year in the analysis, as limited literature exists for projected costs. Because PHEVs have both an electric motor and an engine, they do not receive as many maintenance cost benefits as fully electric technologies. We assume maintenance costs equivalent to conventional vehicles in the Slow Advancement projection because of uncertainty about battery degradation, especially the effects of fast charging.[33] Estimates from Al-Alawi and Bradley (2013) and Mishra et al. (2013) are used for the PHEV and BEV costs respectively for the Moderate projection. The Rapid Advancement projection is based on assumed relative costs guided by consultation with the DOE-VTO and the U.S. Environmental Protection Agency. The conventional LDV maintenance costs are from Al-Alawi and Bradley (2013).

[33] The current literature (Al-Alawi and Bradley 2013; Lowell, Jones, and Seamonds 2016; Propfe et al. 2012) assumes maintenance costs for BEVs and PHEVs to be less than conventional vehicles, but equivalent costs are used as a conservative upper bound.

Table 8. Transportation Maintenance Cost Assumptions (Constant for All Years)

Technology	Corresponding Conventional Maintenance Cost (2016$/ Year)	Relative Maintenance Cost to Conventional Vehicle		
		Slow Advancement	Moderate Advancement	Rapid Advancement
Light-duty auto BEV	374	1.00	0.80	0.50
Light-duty auto PHEV 25	374	1.00	0.94	0.75
Light-duty auto PHEV 50	374	1.00	0.87	0.75
Light-duty truck BEV	533	1.00	0.80	0.50
Light-duty truck PHEV 25	533	1.00	0.89	0.75
Light-duty truck PHEV 50	533	1.00	0.83	0.75
Medium-duty BEV	1,771	1.00	0.70	0.50
Heavy-duty BEV	9,201	1.00	0.70	0.50
Electric bus	28,945	1.00	0.76	0.50

As with LDVs, the maintenance costs for medium and heavy-duty electric vehicles are expected to be less than those of conventional technologies. The conventional vehicle costs in Table 8 were calculated based on per-mile maintenance cost estimates from CARB (2015) and the annual vehicle miles traveled by vehicle type from the Alternative Fuels Data Center (DOE 2015b).[34] The Slow Advancement sensitivity assumes maintenance costs that are equivalent to those of conventional vehicles, the Moderate Advancement sensitivity uses estimates provided by CARB (2017c), and the Rapid Advancement sensitivity assumes half the maintenance cost of conventional vehicles based on authors' assessment. The development of Slow and Rapid maintenance costs for electric buses follows the same methodology used for MDVs and HDVs, and the Moderate Advancement case is based on CARB (2017). Despite the expectation and initial indications that electric vehicles have lower routine maintenance costs, the Slow Advancement sensitivity is equivalent to conventional maintenance cost to account for uncertainties such as battery replacement rates.

[34] As shown in Table 11, these annual mileage assumptions are LDV: 11,346; MDV: 13,116; HDV: 68,115; Bus: 34,053.

2.1.7 Infrastructure

Increased availability of charging infrastructure—such as a widespread public electric vehicle supply equipment (EVSE) network—facilitates electric vehicle market growth (Melaina et al. 2016b). Various charging solutions are possible, including plugging vehicles into EVSE, inductive charging at parking places, vehicle stopping places, or in roadways, or catenary charging provided through a network of wires along routes. Small-scale demonstrations of catenary charging, for example, already exist (Riddett 2015; Williams 2017). Additional information on infrastructure assumptions is included in Appendix A, including dynamic charging infrastructure costs. For this analysis, we consider various levels of charging infrastructure required for each transportation subsector and we calculate a per-vehicle cost to estimate the total system cost incurred from infrastructure buildout. For simplicity, we select plug-in EVSE as the basis for our assumptions, but this is not intended to indicate that other solutions are unlikely.

We assume ratios of the number of LDVs to the number of public and private chargers based on allocations in Melaina et al. (2016),[35] shown in Table 9. We assume ratios of medium- and heavy-duty trucks and buses to the number of DCFCs, based on charger power and battery size,[36] that we estimate would support operational duty cycles that require shorter charging times. Using these costs as the basis for the estimate is not intended as a strong or specific prediction that this charging technology would be deployed at these levels. Although some charging needs could be met by Level 2 charging, for simplicity we capture a range of charging costs through the ratio of vehicles to DCFCs rather than a range of charger types.

Table 9. EVSE to Vehicle Ratios from Melaina et al. (2016)

	DCFC	Community Level 2	Community Level 1	Work Level 2	Work Level 1	Home Level 2	Home Level 1
EVSE Per Million PHEVs (Thousands)	0	2.68	0.60	167	167	327	555
EVSE Per Million BEVs (Thousands)	0.47	11.11	0.43	166	166	328	559

The per-vehicle EVSE costs used for this analysis are displayed in Table 10. Costs for Level 1 and Level 2 charging are based on Melaina et al. (2016), and costs for DCFC equipment are taken from Francfort et al. (2017). Costs are calculated based on a 10-year lifetime for EVSE (DOE 2015c); the actual and future lifetime is uncertain and limited literature is available. Costs include only capital and installation costs. We assume the initial purchase of an EVSE consists of upfront costs that are higher than those for replacement equipment, because many of the installation costs—such as those for wiring and site preparation—would not need to be repeated after 10 years. Therefore, the "New" costs in Table 10 represent the EVSE costs associated with switching from a conventional vehicle to a PEV, and the "Replace" costs represent the EVSE investment required for replacing an EVSE at the end of its lifetime. Additional detail on these calculations is included in Appendix A. We assume constant EVSE costs over time, due to

[35] A recent analysis from Wood et al. (2017) explores non-residential charging needs for LDVs. We use estimates from Melaina et al. (2016) for EFS because it includes both residential and non-residential charging requirements.
[36] See Appendix A for additional detail on the DCFC ratio calculation.

limited literature to support costs trajectories and the relative maturity of electric charging technology. Costs for the EVSE itself are generally assumed to decline, but total costs also depend on future installation costs (DOE 2015c), a significant and uncertain portion of which depends on potentially divergent trends such as learning from experience, regulatory changes, and favorability of sites.

Table 10. Per-Vehicle[a] EVSE Infrastructure Capital and Installation Cost Assumptions

Technology	Slow Advancement		Moderate Advancement		Rapid Advancement	
	New	Replace	New	Replace	New	Replace
Light-duty PHEVs	$2,428	$1,759	$2,024	$1,462	$1,857	$1,338
Light-duty BEVs	$2,523	$1,827	$2,103	$1,518	$1,926	$1,386
Medium-duty BEVs	$34,556	$25,051	$27,645	$20,041	$9,215	$6,680
Heavy-duty BEVs	$136,665	$127,536	$56,944	$53,140	$25,308	$23,618
Electric Bus	$97,618	$91,097	$45,555	$42,512	$12,424	$11,594

[a] Lifetimes of EVSE and vehicles are different, and costs are adjusted accordingly.

2.2 Levelized Costs

The cost and performance metrics for transportation presented in Section 2.1 factor into the projected levelized costs of different vehicle types. To illustrate the relationship between the electric vehicle cost assumptions and those for conventional vehicles, we perform a simple comparative analysis for a subset of technologies using the inputs in Section 2.1. We calculate a levelized cost of driving (LCOD) for each vehicle type based on the projected vehicle capital cost, maintenance cost, infrastructure cost, fuel efficiency, and fuel prices. LCODs of electric and corresponding conventional vehicle technologies are estimated and compared.[37] Actual vehicle LCODs are characterized by significant variations in the market, due to heterogeneous vehicle capital cost and fuel economy (as shown in Figure A-1) as well as different use levels. These comparisons are purely illustrative, and are not meant to assess adoption potential. Additional detail on the LCOD calculation and a sensitivity analysis of input parameters are included in Appendix A. The sensitivity analysis shows that increasing the discount rate makes the electric technologies, which have higher upfront capital costs, less cost competitive compared to conventional vehicles, while increasing the assumed values for mileage or vehicle lifetime makes the electric technologies more cost competitive.

[37] Light-duty cars and trucks are compared to gasoline vehicles, and MDV, HDV, and buses are compared to diesel vehicles.

The goal of this LCOD analysis is to apply a single unified metric for comparison across the different levels of projected advancement in transportation technology costs. We reviewed several LCOD analyses from the literature (Roosen, Marneffe, and Vereeck 2015; Propfe et al. 2012; Aber 2016; Elgowainy, Han, and Ward 2016; Hagman et al. 2016) and developed this LCOD approach to reflect only those cost elements represented in this analysis. The simple LCOD metric has its limitations: it does not estimate variability between different models and driving conditions, does not consider other important factors related to consumer preference (e.g., consumer convenience related to range and refueling time), and embeds the uncertainties in the underlying components. The purpose of the LCOD calculation is not to assess the potential for vehicle adoption, which depends on other factors in addition to costs, but to offer a comparable cost metric that combines the multiple factors described above. Also, the LCOD used here represents only costs included in this analysis, and it omits other costs associated with vehicle ownership, including costs of insurance, depreciation, registration, incentives, and taxes, among others. We also do not distinguish mobility services provided by the different vehicles, but assume that all vehicles types within a vehicle class drive the same annual mileage. Given this assumption, the LCOD of a BEV 100 calculated here may be higher than in reality, because a BEV 100 provides more limited mobility services, and might not be able to cover the same annual mileage of a conventional gasoline vehicle, due to limitations in performing long-distance trips. The LCOD metric should be considered a long-term marginal cost, and it has not been adjusted to reflect prices of vehicles that are being sold today at a loss (Bhuiyan 2017; Ferris 2016; Cole 2014). Conventional vehicle technology cost and performance assumptions are not varied for this simple comparison, despite uncertainty in their values. With these limitations in mind, we calculate LCODs to show when electric vehicle technologies reach cost parity with conventional vehicles, given these projected cost and performance assumptions.

The input assumptions for the LCOD calculation are shown in Table 11. Gasoline, diesel, and electricity prices are based on the AEO 2017 Reference case[38] (EIA 2017a).[39] In keeping with our focus on end use, the analysis presented in the main body of this report uses a 10% discount rate, which is higher than the 3% or 7% often used as a societal discount rate. Vehicle lifetime assumptions are meant to represent the total cost of vehicle ownership at a system level, not from the perspective of the buyer. Figure 13 shows the LCOD for each vehicle technology in the year 2020 for the Moderate Advancement projection, and the breakdown of the LCOD by cost component. Results highlight that in 2020 conventional ICEVs are always the cheapest technology. For LDVs, the BEV 100 is the next cheapest option, assuming equal miles driven for each powertrain. The right side of Figure 13 shows that capital costs represent the majority of total LCOD for LDVs, while fuel costs are more important for MDVs and HDVs. The share of LCOD attributable to capital cost increases as vehicle electrification increases, due to higher battery costs.

[38] The AEO 2017 Reference case we use includes the Clean Power Plan. The AEO 2017 Reference case without the Clean Power Plan has slightly lower electricity prices and nearly identical gasoline and diesel prices; these price changes would have minor effects on our LCOD comparisons.
[39] Examples of fuel price calculations are included in Appendix A.

The following three figures show the relative LCOD compared to conventional vehicles for light-duty cars (Figure 14), light-duty trucks (Figure 15), and MDV, HDV, and buses (Figure 16) for each technology advancement projection. The LCODs of LDVs in 2017 are different for each technology advancement projection due to varying assumptions for maintenance and infrastructure cost for each case.

Table 11. Input Assumptions for LCOD Calculation

LCOD Input	Value	Source
Discount rate	10%	assumption[a]
Vehicle life	LDV: 15 years MDV: 15 years HDV: 15 years Bus: 10 years	EnergyPATHWAYS
Annual vehicle miles traveled	LDV: 11,346 MDV: 13,116 HDV: 68,115 Bus: 34,053	Alternative Fuels Data Center (DOE 2015b)

[a] Discount rate sensitivities are presented in Appendix A.

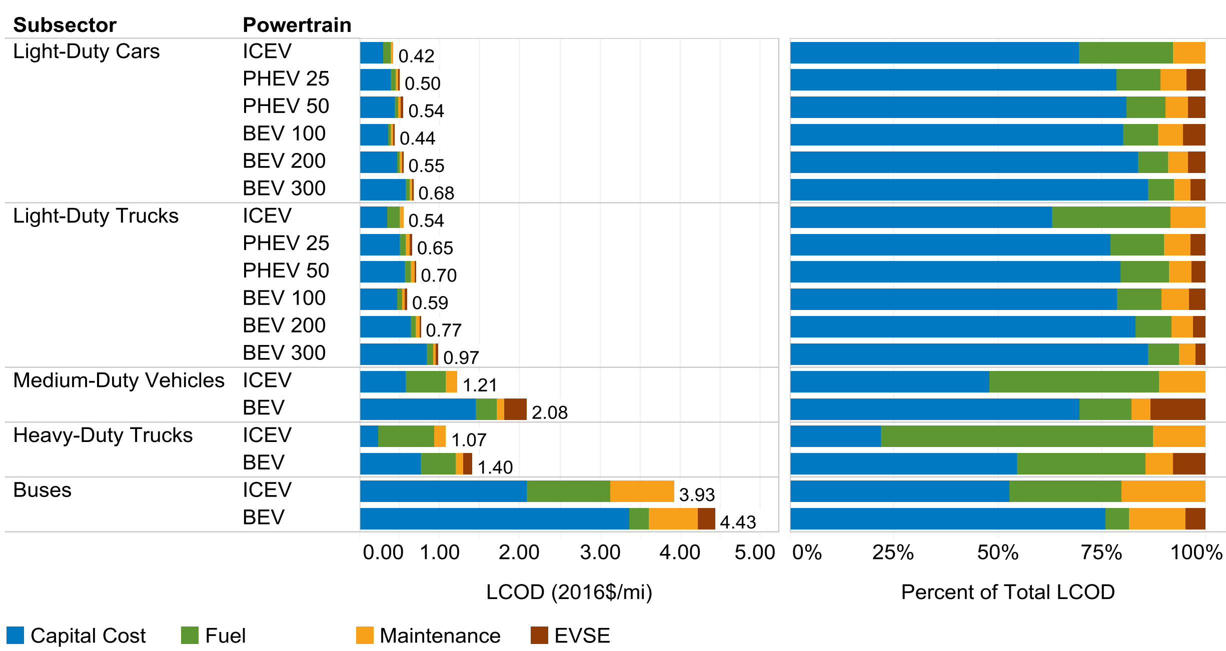

Figure 13. LCOD and percent of total LCOD by cost component in 2020 for the Moderate Advancement projection

Capital cost represents the expected long-term equilibrium vehicle retail purchase price.

All powertrains within each vehicle class are assumed to be driven the same number of miles.

Figure 14 shows how the potential for and timing of cost parity varies with the technology advancement projection for LDVs. Cost parity should not be construed as an indicator of adoption competitiveness, because many other factors influence adoption. The PHEV 25 car reaches cost parity with gasoline vehicles in 2026, and only in Rapid Advancement case, while the PHEV 50 LCOD becomes equivalent to a conventional vehicle in 2050. In the case of the BEV 300 car, cost parity with gasoline vehicles occurs only in the Rapid Advancement scenario in 2034. The lower-range BEV 100 is the first electric drivetrain to reach cost parity in the Rapid Advancement case, in 2021, and is the only drivetrain to reach cost parity in the Moderate Advancement case (in 2025) and the Slow Advancement case (2031), because of its lower capital cost and higher fuel efficiency than the other electric vehicles. However, the limited range of the BEV 100 may add costs not included here. For example, any trips longer than 100 miles would have to be fulfilled by alternative—and possibly more expensive—modes of transportation, or they would have to include a charging opportunity. We do not include these costs because they relate to adoption and vehicle use, which is beyond the scope of this analysis. For light-duty trucks, all technologies reach cost parity in the Rapid Advancement case, occurring in 2021, 2024, 2029, and 2035 for BEV 100, PHEV 25, PHEV 50, and BEV 300, respectively. As shown in Figure 13, fuel costs make up a higher portion of the LCOD for light-duty trucks compared to light-duty cars, so the increased fuel efficiency of electric technologies has a greater ability to outweigh the increase in capital costs. In the Moderate Advancement case, the PHEV 25 reaches cost parity in 2027, and the BEV 100 reaches cost parity 2025. The BEV 100 is the only technology to reach cost parity in the Rapid Advancement case (in 2031).

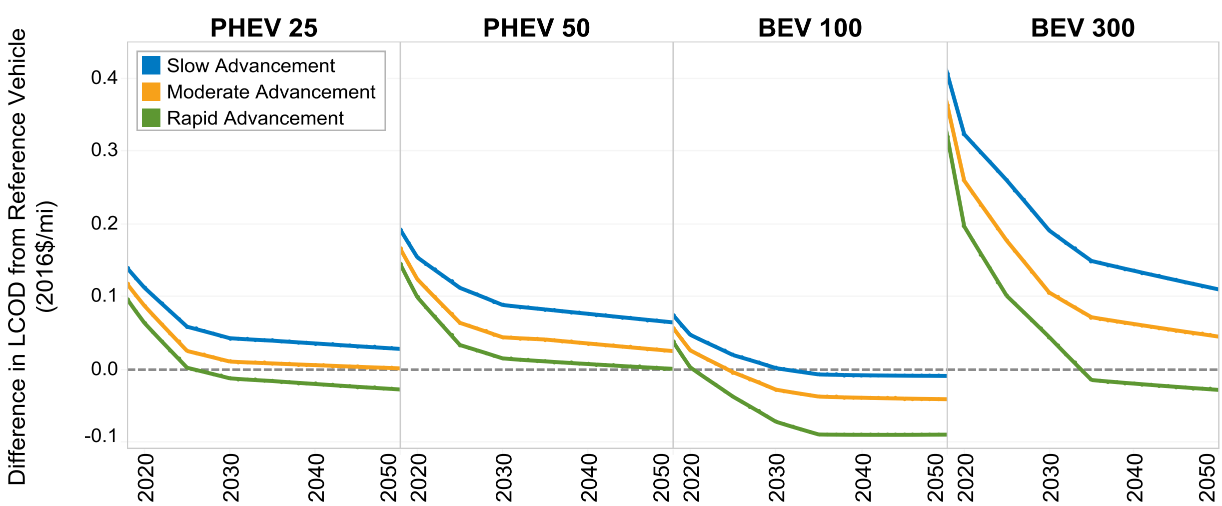

Figure 14. Difference in LCOD from a reference light-duty gasoline car

All powertrains within each vehicle class are assumed to be driven the same number of miles.

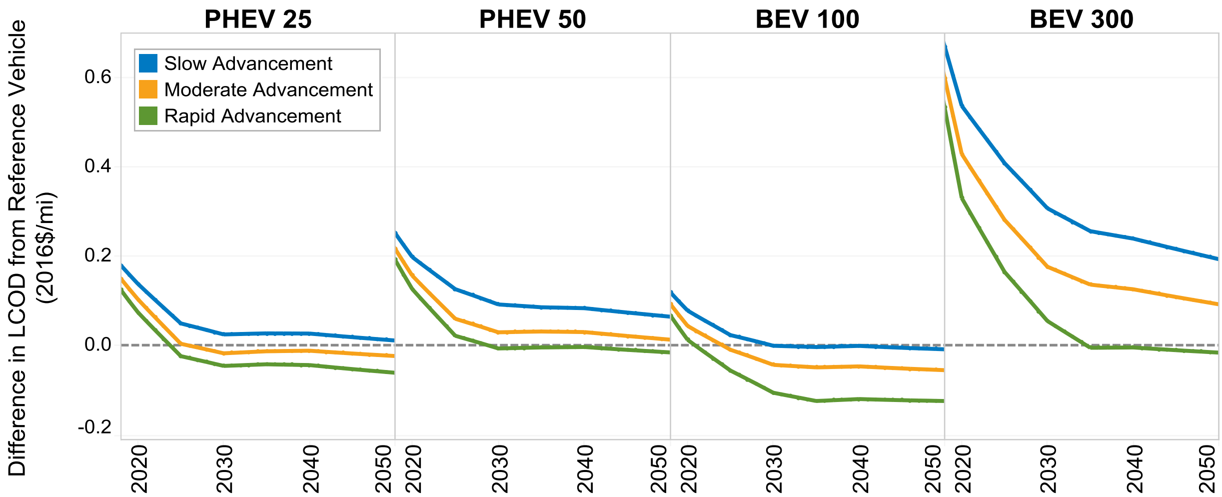

Figure 15. Difference in LCOD from a reference light-duty gasoline truck

All powertrains within each vehicle class are assumed to be driven the same number of miles.

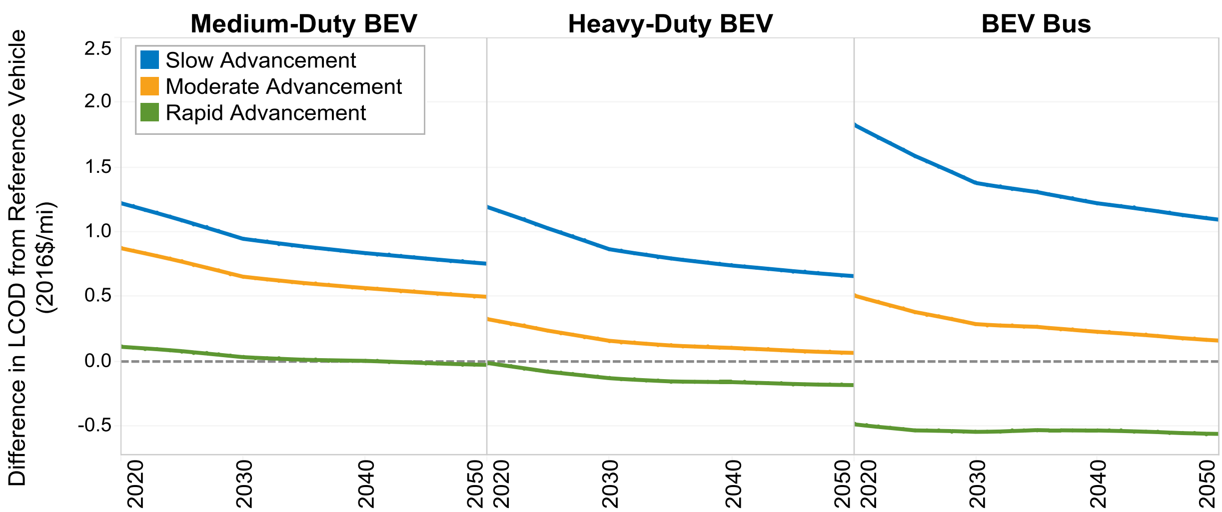

Figure 16. Difference in LCOD for MDVs, HDVs, and buses from a reference diesel vehicle

The potential for cost parity of non-LDV electric technologies in this analysis varies by vehicle class and technology advancement projection. As shown in Figure 16, the LCOD of all of the non-LDV electric vehicles is below that of the comparable diesel vehicle by 2035 in the Rapid Advancement case. The electric vehicles in the Rapid Advancement case are assumed to have shorter ranges; despite the potential near-term cost parity, such a limited range would not be feasible in all applications without a ubiquitous, fast, and reliable recharging network (e.g., extensive dynamic charging).

In the Moderate Advancement case, no technology reaches cost parity, but the battery electric HDV LCOD is similar to that of a conventional vehicle by 2050. Given the high annual vehicle miles traveled for this vehicle class, the fuel cost savings from the increased efficiency of an electric drivetrain offsets the additional capital and infrastructure costs[40]; Figure 13 shows the high proportion of the total HDV LCOD attributed to fuel cost.

In the Slow Advancement case, no technology reaches cost parity with ICEVs. The longer ranges assumed in the Slow Advancement case would cover a much broader range of applications even with a limited recharging network, but the high costs associated with the large batteries needed to meet the longer-range requirement make them less cost-competitive. Our LCOD comparisons are based on the HDV projections and other assumptions presented in this report, but additional research is needed to understand the economic and non-economic costs and tradeoffs for MDVs and HDVs, as well as the precise duty cycle requirements of specific market segments.

The levelized cost results presented here show the relationship of the different costs components for the in-scope vehicle technologies, but they do not fully explain the potential for vehicle adoption, which is also driven by consumer preference and vehicle characteristics other than cost.[41] Moreover, the LCODs, like the costs on which they are based, do not encompass the full diversity of vehicles and vehicle use or the range of vehicle prices in a mature market. For example, Figure 17 shows the range of the manufacturer's suggested retail price (MSRP) for model-year 2015 conventional LDVs,[42] reflecting the many model options that exist for conventional vehicles and the wide range of prices.

This analysis does not estimate the effects of additional barriers and drivers on the electrification of the on-road transportation fleet. Consumer choice for LDVs is a widely researched area, and it often includes factors besides costs, such as range, driving experience, vehicle volume, refueling experience, emissions, noise, and personal choice. Vehicle selection for MDVs, HDVs, and buses considers detailed service timing, weight, volume, and duty cycle requirements that may limit or preclude electric vehicles adoption when their charging time cannot be accommodated or when the battery weight, volume, and performance do not meet vehicles' functional requirements. Conversely, electric vehicles have received federal and state public incentives, and these favor adoption (DOE 2017b). Additional policy drivers such as the zero emission vehicle mandate, potential ICEVs bans, and city initiatives for clean mobility solutions (Nelson 2017; Berg 2017; Castle 2017) also support increased adoption of electric vehicles, but these considerations are beyond the scope of this analysis.

[40] For example, using the 2025 HDV efficiencies and the discount rate-weighted average AEO fuels prices ($4.24/gge for diesel and $4.59/gge for electricity), a battery electric HDV would save over $15,000 in fuel costs per year when driving 68,000 miles per year. The mileage assumption is based the Alternative Fuels Database (DOE 2015b).

[41] Liao, Molin, and Wee (2017) provide a review of consumer choice literature in the context of electric vehicles; Brooker et al. (2015) detail the assumptions of the Automotive Deployment Options Projection Tool (ADOPT) vehicle choice model.

[42] The costs of non-conventional vehicle powertrains also vary, but fewer makes, models, and trims are currently available. We expect a similar or greater range in MSRP as conventional vehicles as more PEV model options enter the market. Appendix A includes the range of MSRP and fuel economy for all MY 2015 light-duty vehicle powertrains.

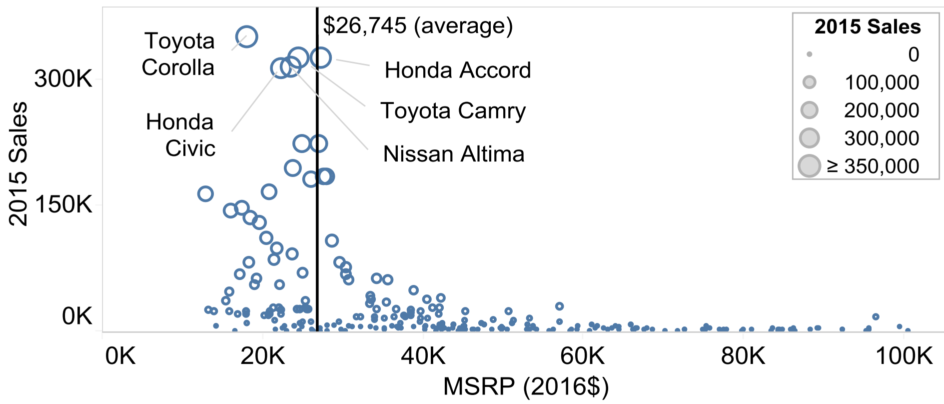

Figure 17. Model-year 2015 conventional vehicles by sales and MSRP, with sales-weighted average MSRP (vertical grey line)

Sources: Wards Automotive (MSRP) and IHS Automotive (sales)

Data were compiled for the NREL Automotive Deployment Options Projection Tool (ADOPT) vehicle choice model (Brooker et al. 2015) by Russ Campbell, CSRA Inc.
Vehicle models with an MSRP exceeding $100,000 are not shown.

3 Buildings

The residential and commercial buildings sectors, which in aggregate comprise 39 quads (or 40%) of total primary energy consumption, account for the largest share of primary energy consumption in the United States. Nonetheless, the combined sectors account for the smallest share (29% or 20.8 quads) of total final[43] energy consumption. This difference arises from the fact that the residential and commercial buildings sectors are the most electrified of the consuming sectors—electricity makes up 43% and 61% of total final energy consumption in the residential and commercial sectors respectively.[44, 45] The remaining share of final energy consumption is comprised of a mix of fossil fuels—natural gas, liquefied petroleum gas (LPG or propane), and distillate fuel—as well as a small amount of district heat or steam within the commercial buildings sector.

As shown in Figure 18 and Figure 19, space heating, water heating, and cooking account for most of the fossil fuel use in residential and commercial buildings. In 2009, approximately 4.7 quads of natural gas, 0.6 quads of fuel oil, and about 0.5 quads of propane were used directly in the residential sector, with almost all that use occurring in space and water heating (EIA 2009). Cooking (both indoor and outdoor), clothes drying, and other uses (shown in the "other" category of Figure 18), which include pool and hot-tub heaters, generators, and other small motors (e.g., lawn mowers), account for the remaining share of direct fossil fuel use.

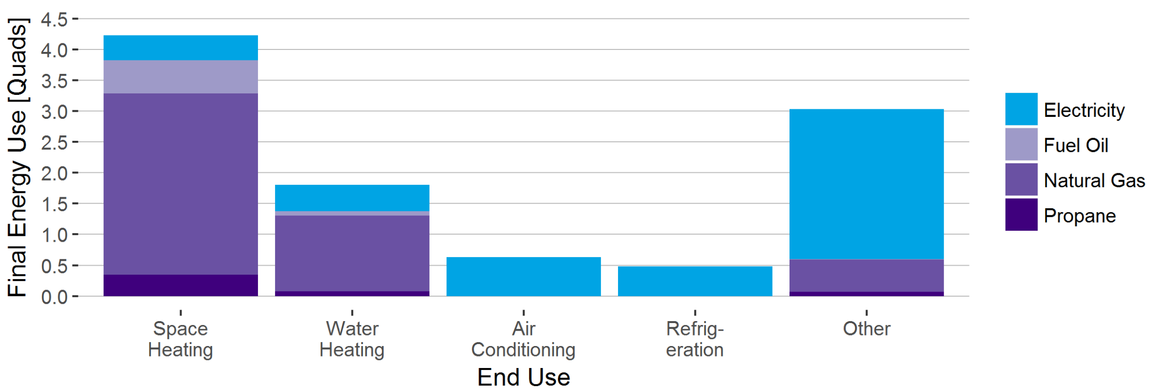

Figure 18. Final (or site) energy use in residential buildings by end use and fuel type: 2009 RECS

In the commercial buildings sector, a similar heavy reliance on natural gas and fuel oil is seen for space heating, water heating, and cooking (Figure 19). Replacement of these fossil fuel uses represents a significant potential for electrification in the residential and commercial buildings sector, particularly in the space and water heating end uses. Accordingly, this analysis focuses on

[43] "Final" energy refers to energy consumed at the point of use. It does not include upstream conversion losses. For example, final energy includes the energy content of electricity consumed on site, but it does not include the energy content of fuel used to generate the electricity. In the residential and commercial buildings sector, this is often referred to as "site" or "on-site" energy.
[44] Primary energy consumption metrics distribute the energy required to generate electricity to the consuming sector. The relative inefficiency of electricity generation in the United States and the high share of electricity consumption in buildings make the combined residential and commercial buildings sector the largest consumer of primary energy.
[45] Data are from the 2009 RECS and 2012 CBECS at https://www.eia.gov/consumption/data.php, which was accessed August 2017.

space and water heating end uses in its development of cost and performance projections for the residential and commercial buildings sectors, and in particular on projections for electric heat pump technologies.[46]

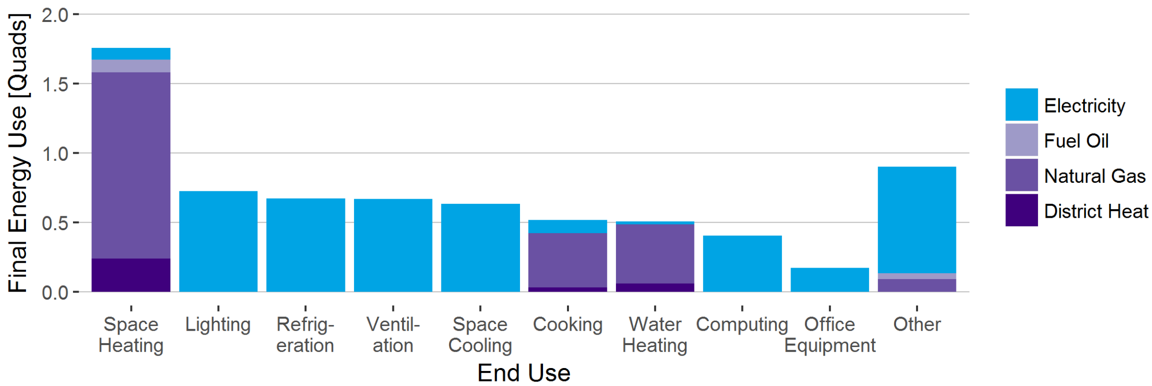

Figure 19. Final energy use in commercial buildings by end use and fuel type: 2012 CBECS

3.1 Residential and Commercial Buildings Cost and Performance Sensitivities

For the residential and commercial buildings sector, we develop scenarios of the future cost and performance of heat pumps for space heating and water heating applications. As with the transportation sector assessment, the EFS modeling framework includes a representation of all major end uses in the buildings sectors and a suite of technologies that provide those end-use services; however, given the EFS focus on the potential and impacts of electrification, our analysis of buildings technologies focuses on the end uses and associated technologies that demonstrate the largest potential for electrification: heat pumps for space heating and water heating (Table 1). The cost and performance parameters developed for these technologies are described in the remainder of this section. For each technology and end use, we develop parameters for the total installed cost (including retail cost and installation), efficiency, lifetime, and maintenance cost, but we limit our presentation to the installed cost and efficiency results. The remaining parameters are used to calculate the levelized cost of service metrics presented in Section 3.2, and are themselves detailed in Appendix A. For all other end-use technologies that create opportunities for electrification (e.g., induction cook-tops and electric clothes dryers), we rely on the default model inputs to EnergyPATHWAYS, the accounting tool used for the EFS,[47] which are largely based on assumptions from the NEMS Residential Demand and Commercial Demand modules (EIA 2017b, 2017c). Similarly, for the efficiency of space cooling from air-source heat pumps, we rely on default assumptions from EnergyPATHWAYS.

[46] Natural gas (or other fossil-fuel) heat pump technologies also exist and can substantially increase the efficiency of space and water heating relative to conventionally fueled furnaces or boilers; however, only technologies that provide opportunities for electrification are considered in this report, and thus natural gas heat pumps are not explored.

[47] A forthcoming report in the EFS series will document the use of the EnergyPATHWAYS framework in the study.

3.1.1 Buildings Literature Review

The cost and performance projections for residential and commercial heat pump technologies (for space heating and water heating) developed in this analysis are similar to the transportation technology projections in that they were developed based on a review of academic and technical literature, as well as of data inputs (or outputs) from existing energy models that include estimates of current or projections of future adoption, costs, and characteristics of buildings technologies or end-use devices. Few projections of the future costs and performance of buildings technologies exist in the literature, particularly over the time horizon assessed within the EFS (present day to 2050). Furthermore, sources that do provide projections often note the large amount of uncertainty in projected values (Desroches et al. 2013). Accordingly, the projections presented here are grounded in estimates from recent literature, but necessarily extrapolate from those estimates to create comprehensive projections of technology parameters that are consistent with today's technology prices and efficiencies and extend to 2050.

Projections of technologies for which relatively few estimates of future cost and performance exist were developed based on the results of targeted searches and in consultation with buildings analysts from DOE and several national laboratories. Where literature and expert opinion do not offer sufficient data, we develop our own speculative assumptions based on observed trends in equipment and appliance standards, research and development activity, and equipment evolution. As a result, the cost and performance sensitivities developed under this effort do not represent predictions of the future costs and performance of technologies, but rather alternative pathways of technology development that could occur with varying degrees of investment in R&D, technology breakthroughs, and other drivers of innovation.

Our review of academic and technical literature identified five key sources of cost and performance data for residential and commercial buildings technologies. First are the suite of Technical Support Documents (TSDs) associated with the development and implementation of the federal appliance and equipment standards. The DOE Buildings Technology Office (DOE BTO) Appliance and Equipment Standards Program is responsible for developing and implementing minimum energy conservation standards for over 60 categories of residential and commercial appliances and equipment. Data and analysis supporting the development of the standards are detailed and published in TSDs (DOE 2009, 2015a, 2016c, 2016d). These documents contain in-depth analyses and reporting of the current costs and performance parameters of technologies, and in some cases, they present projections of future costs of each technology at associated efficiency or performance levels. These projections are typically developed through analysis of experience or learning curves (Taylor and Fujita 2013; Desroches et al. 2013).

The experience curve method relates the real cost of production of a manufactured product to its cumulative production, or "experience." As cumulative production increases, the cost of producing the next product declines. The rate at which cost declines with production is known as the "learning rate" and is defined as the percentage reduction in cost associated with each doubling of cumulative production. The DOE BTO standards program, in some cases, develops multiple fits of the relationship between cumulative production and cost and the associated learning rate. When useful, we apply these alternative fits in the development of our projections.

Second, the DOE BTO Emerging Technologies Program funds and executes R&D activities to advance high-efficiency buildings technologies. In order to guide and optimize their research programs, DOE BTO develops targets for the future cost and performance of emerging technologies (DOE 2014c, 2014b, 2016b; CCHRC 2013).[48] These targets are expected to be achieved under the current research program, and thus represent estimates of near- to mid-term expected improvements in cost and performance of emerging technologies, including advanced heat pump technologies. In addition, each R&D effort funded by DOE BTO produces technical reports that detail successful technology improvements and identify the potential impact of the research on the future cost and performance of the technology (Baxter 2017b; Mahmoud 2016; Shen 2017; Verma 2017; Messmer 2015; Gluesenkamp 2016). These impacts provide another indication of the potential for improvements in cost and performance associated with technology breakthroughs.

Third, several industry associations, consulting companies, and research organizations, such as the Northwest Energy Efficiency Alliance, the Northeast Energy Efficiency Partnerships (NEEP), Navigant Consulting, Inc., Cadmus Group, and Energy and Resource Solutions execute a broad range of technology and market analyses on existing and emerging energy-efficient technologies, including heat pumps for space and water heating applications (Navigant 2015, 2016; NEEA 2015; Cadmus 2016; NEEP 2011, 2012, 2013, 2014, 2016, 2017a, 2017b). These studies characterize cost and performance of technologies, present reviews of current market conditions—based on surveys, efficiency program reviews, and historical data analysis—and identify potential opportunities and barriers for market growth. These studies typically do not provide explicit projections of future cost and performance—only current or near-future values—but they do qualitatively identify the cost and performance improvements needed to achieve market penetration goals.

Of these studies, two were particularly relevant for this analysis: the series of "incremental cost studies" by NEEP and the study reported in *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies* by Navigant (2016) in support of EIA's NEMS model (EIA 2009, 2017b, 2017c). The studies carried out by NEEP estimate the incremental cost of efficiency measures (e.g., purchase and installation of an air-source heat pump) relative to a baseline technology (e.g., a gas furnace plus a room air conditioner) based on data collected from consumers, manufactures, installers, and efficiency program administrators. These reports cover a wide range of measures, including residential and commercial air-source heat pumps and heat pump water heaters (HPWH), among many other technologies or efficiency measures.

[48] BTO specifies targets in different units depending on the technology. For example, air-source integrated heat pump targets are specified in terms of installed cost premium per square foot and efficiency targets are specified in terms of primary energy seasonal coefficient of performance. As such, we convert these targets into unit-costs and final energy seasonal coefficient of performance. Details of this conversion are shown in Appendix A.

The Navigant (2016) study reviewed literature, performance standards, reported prices, and manufacturing costs to develop projections of residential and commercial buildings technologies costs and performance characteristics to inform the development of assumptions for the Residential and Commercial Demand Modules of EIA's NEMS. This report provides both current and projected cost and performance characteristics for most major residential and commercial end uses, including space heating, space cooling, water heating, cooking, lighting, cloths washing and drying, and refrigeration/freezing. The report presents a range of projected values for the future that are loosely tied to alternative adoption scenarios. The Navigant-led analysis, in many ways, used a similar approach to that implemented here—namely, review and compile data on existing and projected future costs from academic and technical (or gray) literature to develop projections for a modeling application. Data gaps were filled based on expert opinion or analyst assessment.

The outcomes from the Navigant (2016) study that are used to inform the parameterization of the NEMS input assumptions contain some level of interpretation or choice by an analyst, such as averaging of values from the Navigant data set or choosing the minimum or maximum value. Thus, for this analysis, we treat the Navigant outcomes as a source in addition to the NEMS inputs.

Fourth, the International Energy Agency (IEA) carries out several activities that support the advancement of energy-efficient technologies and measures. We highlight two initiatives of particular relevance to this analysis. The IEA, at the request of the leading industrial nations of the G8, developed a series of roadmaps for renewable and energy efficiency technologies 2050. The *Energy-Efficient Buildings: Heating and Cooling Equipment Roadmap* (IEA 2011) identifies ranges for the improvements in the cost and performance of heat pump technologies (for both space and water heating) for energy and emissions savings through 2050. We use these technology improvement pathways in the development of the Moderate and Rapid Advancement cases presented below.

The IEA also maintains an entire program dedicated to the advancement of heat pump technologies—the IEA Technology Collaboration Programme on Heat Pumping Technologies and Heat Pump Centre. The center provides in-depth data, analysis, and reporting on heat pump technologies, applications, and markets. We leverage cost and performance data as well as market and adoption data from multiple reports from the center (Baxter and Groll 2017a; Groff 2014; Melissa Lapsa and Khowailed 2014).

Finally, for residential building technologies, the National Renewable Energy Laboratory developed the National Residential Efficiency Measures Database–a database of the cost of energy efficiencies measures (Roberts et al. 2012). It includes estimates of the average (and minimum and maximum) current installed costs of a suite of residential energy efficiency measures, including the installation of air-source heat pumps and HPWHs.

Based on these data sources and additional sources identified below, we develop projections of the retail cost, installed cost, efficiency, lifetimes, and annual maintenance costs of heat pump technologies for space conditioning and water heating.

3.1.2 Residential Buildings

Residential Space Heating

The largest use of energy in residential buildings is space heating, which comprises 42% of all residential final energy consumption (EIA/RECS 2009). Furthermore, residential space heating demands are largely met through the combustion of natural gas, LPG, or fuel oil, which account for over 90% of residential energy consumption for space heating (EIA/RECS 2009). As a result, space heating represents the end use with the single-largest potential for electrification in the residential sector.

There are two general types of electric devices for space heating in the U.S. market: (1) electric resistance-based heaters, which rely on heat released when current is run through a conductive material[49] and (2) heat pumps, which, similar to air-conditioning units, move heat (or energy) from one reservoir (e.g., air outside a house) to another reservoir (e.g., air inside the house). Because heat pumps move energy rather than convert potential energy (electricity or other fuel) to heat, they can have efficiencies three to four times greater than a simple resistance-based heater and therefore much lower operating costs. As a result, heat pump technologies, and in particular, air-source heat pumps (ASHPs), have been growing in popularity in the United States. From 1979 to 2012, the share of new homes built with a heat pump in the United States grew from 17% to 49% for multifamily homes and from 25% to 38% for single-family homes (M. Lapsa and Khowailed 2014). As of 2015, the share of heat pumps for new single-family homes had risen to 41% (Melissa Lapsa et al. 2017b).

As of the end of 2015, 11% of homes in the United States used heat pumps for their primary heating needs (EIA 2015). However, these homes are predominantly located in warmer climate regions in the United States—90% of homes that use heat pumps as their primary heating source are in mixed, hot, or marine climates (EIA 2015; Baechler et al. 2015). This is because the efficiency or performance of ASHPs declines with outdoor temperature, and the decline can substantially impact the cost of operating the heat pump, particularly if electric resistance is used as a backup heating source. Thus, future adoption of ASHPs will depend not only on their cost (and the cost of electricity) but also their performance, particularly in colder regions.[50] Given the importance of improving the performance of ASHPs in colder climates, DOE and other private and public institutions (NEEP 2017a, 2017b) are investing in research, development, and deployment of improved cold climate heat pumps (ccASHP).[51,52] Another heat pump type, ground-source (or geothermal) heat pumps, has generally much better performance in colder climate areas than ASHPs. But, owing to their higher cost than ASHPs, ground-source heat

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[49] Electric resistance-based heaters include baseboard radiators (direct radiative heating from electric coils), electric resistance furnaces (ducted hot-air heating), and electric resistance boilers (coupled with baseboard or other radiators).

[50] Additional non-cost barriers or challenges could also impact future adoption. These include noise levels of heat pumps, response time, and general acceptance by customers and installers.

[51] We use "ASHPs" as a general term encompassing all air-source heat pumps, and use "ccASHPs" when referring to cold climate heat pumps.

[52] See for example, DOE BTO research and development projects: "Split-System Cold Climate Heat Pump" (https://energy.gov/eere/buildings/downloads/split-system-cold-climate-heat-pump) and "Residential Cold Climate Heat Pump with Variable-Speed Technology" (https://energy.gov/eere/buildings/downloads/residential-cold-climate-heat-pump-variable-speed-technology).

pumps only account for about 10% of total annual heat pump shipments (Melissa Lapsa et al. 2017a) and, as a result, we do not consider them within this analysis. In addition, multi-function or integrated heat pumps that can supply space heating, space cooling, and water heating from a single device are the focus of active research, and initial prototypes are being field tested (Baxter 2017a). These devices show much promise; however, limited data on cost and performance exists, and the EnergyPATHWAYS framework does not explicitly represent this technology. Thus, we focus here on ASHPs.

Our projections for residential ASHPs are developed based on the data and trends summarized in the suite of sources described above. Given that the performance of ASHPs is highly dependent on ambient temperature and humidity conditions, we develop separate performance projections for ASHPs installed in moderate and warm climates and those installed in cold climates. Efficiency values shown reflect the seasonal coefficient of performance (SCOP) for heating.[53] For the projections, the ASHP efficiencies reported are intended to reflect the performance of a system within the Air Conditioning, Heating, and Refrigeration Institute (AHRI) Climate Zone IV, which is similar to the International Energy Conservation Code (IECC) Climate Zone 5.[54] The efficiencies reported for ccASHP reflect the performance of a system within AHRI Zone V.[55] The cost data shown represent the total installed cost, including the retail purchase price and all costs associated with the installation. We assume cost trends for ASHPs and ccASHPs will follow the same trajectory, and thus the cost projections shown apply to both moderate/warm climate ASHPs and ccASHPs. Historical and current data include a mix of system types but are predominantly for mini-split or multi-split heat pumps. The projections we develop are intended to nominally represent a split-system unit, as such units make up the large share of today's growing market.

[53] The SCOP is calculated as the total heating delivered by a device over the heating season divided by the total energy consumed by the device. SCOP can be converted to heat season performance factor (HSPF), another commonly used performance metric using the following formula: HSPF = SCOP x 3.412.
[54] See Appendix B for a map of the IECC climate zones.
[55] AHRI Zone IV and IECC Climate Zone 5 represent a band of land area stretching across the United States from northern California through the Midwest (Nebraska and Iowa) to the mid-Atlantic (ANSI/AHRI Standard 210/240). AHRI Zone V corresponds to IECC Climate Zone 6 and includes the Northeast, upper-Midwest, and northern Rocky Mountains.

Figure 20 shows a sample of the cost and performance data collected from the suite of literature sources, as well as the residential ASHP projections developed for this analysis. The figure demonstrates the breadth in the range of estimates for both the installed costs and the efficiencies of ASHPs. For example, the TSD associated with the development of the DOE ASHP standards reports costs for split-system heat pumps with 11 different efficiency ratings and finds current installed costs ranging from approximately $4,600/unit to almost $6,000/unit for three-ton units. Variation in costs reflects real-world differences in system efficiency, size (or capacity),[56] type—mini-split, multi-split, or ducted—as well as the difficulty associated with the installation. Installation costs can vary substantially, depending on whether the device is installed in a new or existing home, the age of the home, the availability of ducting (for ducted or multi-split units), the type of incumbent heating system, and the potential requirement to upgrade electric service.

From the bulk of the literature reviewed, the reported efficiencies of currently available or installed (non-cold climate) ASHPs generally range from a seasonal coefficient of performance (SCOP) of approximately 2 to 3 (an HSPF of 6.8 to 10.2); however, NEEP's most recent update of the data available for air-source heat pumps lists existing models with SCOP ratings as high as 4.4 (HSPF of 15) and 85 units with ratings of 3.5 or higher (HSPFs > 12).[57] SCOPs for installed ccASHPs are generally reported in the range of 1 to 2 (Williamson and Aldrich 2015), but NEEP lists available ccASHPs with coefficients of performance at 5°F of 3.

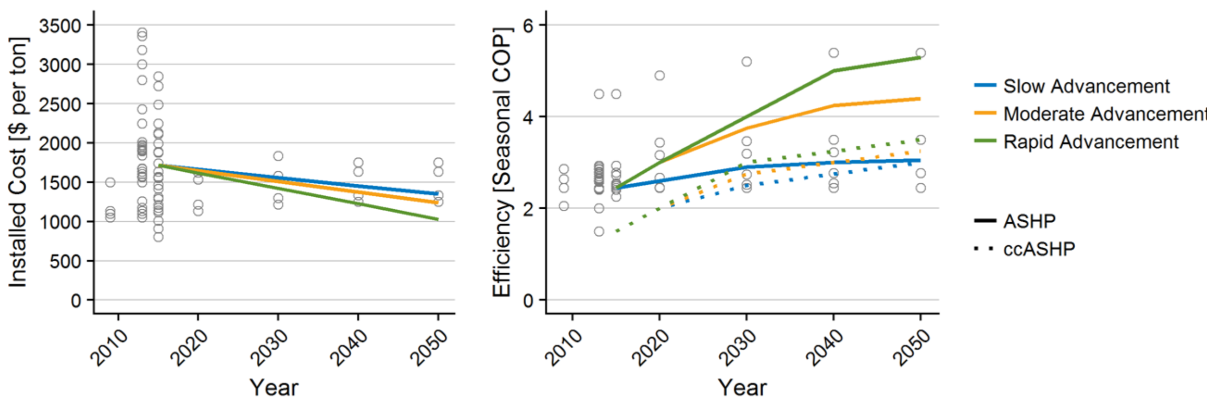

Figure 20. Installed unit costs (left) and performance projections (right) for residential ASHPs for space heating applications

Dots indicate data from the literature, and lines show projections developed in this analysis.

[56] Costs are normalized to dollars per ton of heating capacity, but economies of scale will generally reduce the per-ton cost of higher capacity systems relative to lower capacity systems.
[57] The NEEP data were accessed via "Cold Climate Air Source Heat Pump," http://www.neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump. Accessed 10/30/2017.

Initial values for the cost and efficiencies of ASHPs were based on the averages of the values reported from literature. Data for which we could *not* obtain cost, performance, or system size metrics were excluded from the calculations. Costs for ccASHPs were assumed to be equivalent for ASHPs and ccASHPs, but efficiencies were assumed to be substantially different. The projected installed costs were calculated using the starting values calculated in the 2016 residential heat pump standards TSD (DOE 2016d), with the Slow Advancement and Moderate Advancement cases corresponding to the default (or "medium") and "high decreasing" learning rates respectively. These learning rates equate to average annual reductions in the installed costs of approximately 0.7% and 1%. The Rapid Advancement case assumes the cost reduction goals identified in the IEA technology roadmap (IEA 2011) are achieved by 2050. Under this scenario, average annual reductions in the cost of ASHPs equate to just less than 1.5%.

For the ASHP efficiency projections, the Slow Advancement case follows the efficiency trajectory of the AEO 2017 Reference case. Under the Moderate Advance case, it is assumed that steady technology development—potentially including use of variable speed compressors and refrigerant flow, multi-stage compressors, and advanced refrigerants (DOE 2014b)—leads to sufficient improvements such that the efficiency of a typical ASHP adopted in 2050 is equivalent to the highest efficiency model available today, which is a SCOP of 4.4. Under the Rapid Advancement scenario, we assume substantial successes in R&D—including advanced compressor technologies, advanced refrigerants, and potentially non-vapor compression technologies (DOE 2014a)—yield devices that begin to reach the maximum potential efficiency for vapor-compression systems, which is a SCOP of 5.3 or approximately 45% of the Carnot efficiency.[58]

For ccASHPs, the projections are based on assumptions about the timing of achievement of DOE BTO technology targets. Currently, DOE BTO has a target of developing ccASHPs that achieve a coefficient of performance of approximately 3 at an ambient temperature of -13ºF (DOE 2014b, 2016b) by 2020.[59] Recent research has demonstrated substantial progress towards this target (Baxter and Groll 2017a, 2017b; Shen 2017; Korn, Walczyk, and Jackson 2017; Messmer 2015). We assume that under the Slow Advancement case the technology progresses but the DOE goal is not achieved until 2050. Under the Moderate Advancement case, in a fashion similar to the ASHP, advances in compressor technology, refrigerants, and defrost cycling allow the DOE goal to be achieved by 2040 with continued advancements through 2050. Finally, under the Rapid Advancement case, near- to mid-term breakthroughs allow achievement of the goal by 2030 with continued improvements through 2050.

Residential Water Heating

Water heating comprises the third-largest share (18%) of final energy consumption and the second-largest use of fossil fuels (24%) in the residential buildings sector (RECS 2009). As of 2015, electric water heaters—largely resistance heaters but also HPWHs—were the main source of water heating in 45% of US homes, up from 41% in 2009.

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[58] Assumes an ambient temperature of 48ºF and output temperature of 95ºF

[59] In addition to the performance target, DOE BTO also identifies a target for the maximum decrease in heat pump capacity of 25% at -13ºF.

Electric HPWHs, despite having current efficiencies of 3.0–3.5 times greater than resistance-based heaters, make up a very small share of installed electric water heaters. As of 2012, they represented only 1% of the market (M. Lapsa and Khowailed 2014); however, interest in residential HPWH has grown as more manufacturers have entered the U.S. market. From 2006 to 2016, sales of residential HPWH grew from approximately 2,000 units to over 52,000 (Groff 2014). As of 2016, 12 manufacturers offered ENERGY STAR®-qualified HPWHs.[60]

Figure 21 shows the cost and performance data collected from the suite of literature sources reviewed for residential HPWHs, as well as the three projections developed in this analysis. Efficiencies are reported as "energy factors," which effectively define the amount of energy transferred into the water (or amount of hot water created) per unit of energy consumed. Energy factors for conventional resistance based water heaters are generally greater than 0.9 and often close to 1.0.

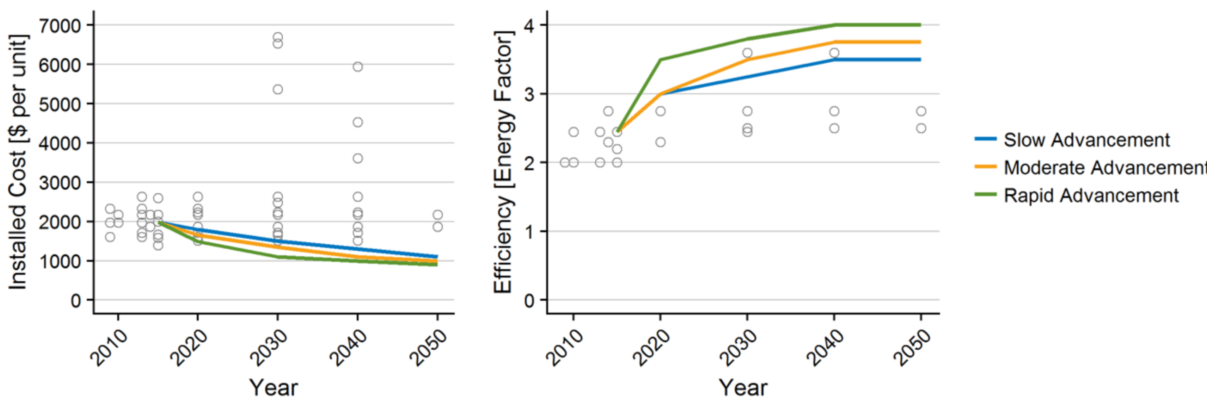

Figure 21. Installed unit costs (left) and performance projections (right) for residential HPWHs

Installed costs include both capital and installation costs. Costs are shown for a 50-gallon HPWH.

Among the sources examined, current installed costs of a HPWH ranged from $1,400/unit to $2,630/unit, depending on the tank volume and efficiency. We assume an initial installed cost of $1,990 based on an average of reported costs. Standards for HPWHs and other domestic water heating devices were developed in 2009 (DOE 2009). The TSD for the development of domestic water heating devices did not include an analysis of technology learning or any other forecast of changes in the future cost of devices. Instead, the DOE (2009) analysis of the costs and benefits of appliance standards adoption for water heating assumed constant prices through time. As a result, we develop our cost projections based on assumed timing of meeting the DOE BTO cost target for non-carbon dioxide. vapor-compression HPWHs, which is defined as an incremental cost of $500 per unit relative to a resistance storage water heater, or a total installed cost of $1,100. Under the Slow Advancement case, steady reductions in cost lead to achievement of the cost target by 2050. Under the Moderate and Rapid cases, cost reductions are achieved more quickly and results in target costs being reached in 2040 and 2030 in the Moderate Advancement and Rapid Advancement cases respectively.

[60] A list of ENERGY STAR-certified water heaters can be found at https://data.energystar.gov/Active-Specifications/ENERGY-STAR-Certified-Water-Heaters/3gp2-af4x/data.

Energy factors of HPWHs reported in the literature range from 2.00 to 2.75; however, the database of ENERGY STAR-certified HPWHs lists over 100 models with energy factors greater than 3.0, and some models as high as 3.5 are reported. On this basis, the assumed 2015 energy factors for HPWHs for this analysis is 2.5, and quickly rises to 3.0 by 2020 across the Slow and Moderate cases and to 3.5 in the Rapid case. Under the Slow case, energy factors of typical units converge to 3.5 by 2040. Under the Moderate case, through continued advancement in compressor technologies and storage tanks, energy factors of typical units converge to 3.5 by 2030 and advancement continues to 2050. Finally, under the Rapid case, energy factors of 3.5 are achieved by 2020 and continued breakthroughs lead to units with energy factors of 4.0 by 2040, which is equivalent to the IEA technology roadmap (IEA 2011) performance improvement targets.

Residential HPWHs are typically placed within the heated space of a home (and draw air from the heated space). Therefore, the effects of climate on performance are small relative to ASHPs for space heating (which draw air from outside). However, because HPWHs are typically located within the heated space they have a negative impact on space heating, as the cool exhaust air is expelled into the home. As a result, HPWHs located in a heated space increase the load on any space heating device. Within the EFS, this effect is captured dynamically within the EnergyPATHWAYS modeling framework by altering the heating service demands for homes that adopted HPWHs.

3.1.3 Commercial Buildings

Commercial Space Heating

Space heating is the single-largest use of energy in the commercial buildings sector, accounting for 25% of all final energy use and 60% of all fossil fuel use. As of 2012, electricity accounted for less than 5% of energy use for space heating in commercial buildings. Commercial space heating thus represents a substantial opportunity for electrification through the increased adoption and use of high efficiency air-source heat pumps.

In small commercial spaces, residential ASHP units with capacities up to 60 kBtu/hour (or five tons) can be applied; however, in larger commercial buildings (e.g., schools, hospitals, large offices, warehouses), units with much greater heating capacity must be used. Commercial systems can range in capacity from 5 tons (60 kBtu/hr) for small stores and offices to over 60 tons (760 kBtu/hr) for hospitals, warehouses, or other larger commercial buildings. Thus, for the EFS we develop Slow Advancement, Moderate Advancement, and Rapid Advancement projections for commercial-scale ASHPs for space heating applications. Given that the unit size or capacity of commercial ASHP systems can vary significantly with building type and size, our projections specify installed costs per heating capacity per hour ($/kBtu/hour), as opposed to cost per unit for a specific size unit.

Figure 22 shows the source data as well as our projections for the Slow, Moderate, and Rapid Advancement cases. Current costs compiled from the literature show a substantial amount of variation, despite a relatively tight range in efficiencies. This is likely due to the large potential for differences in the capacities and associated economies of scale for commercial systems.

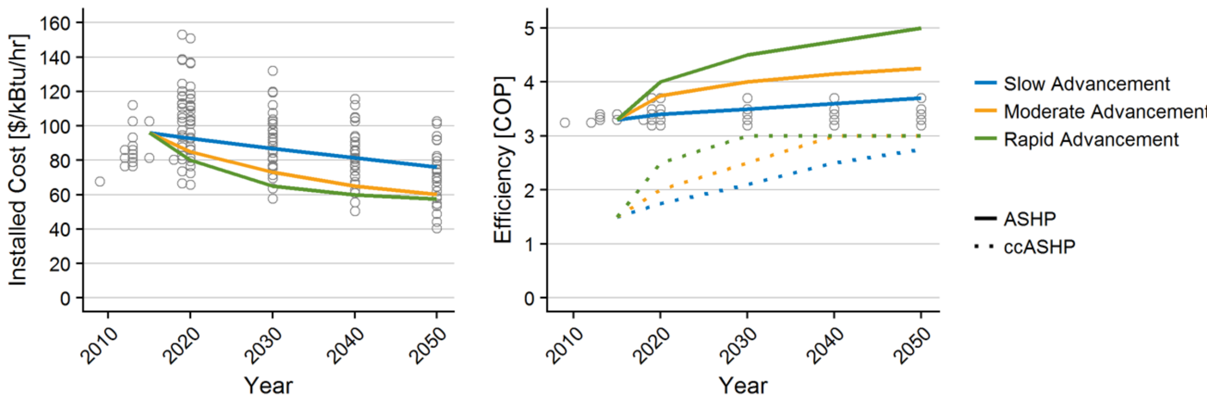

Figure 22. Installed unit costs (left) and performance projections (right) for commercial air-source heat pumps

Installed costs include both capital and installation costs.

For our projections, starting values are based on averages of the suite of cost and performance values obtained from the literature. Projections of future installed costs are based on a combination of the price trends (learning rates) estimated in the TSD for the development of commercial heating equipment standards (DOE 2015a) and the IEA technology roadmap targets (IEA 2011). The reference scenario in the TSD used a constant price trend (i.e., zero cost improvement). We find this scenario to be overly conservative given that commercial ASHPs represent an area of active research. So, we instead use an estimated *decreasing price* scenario, which results in an average annual rate of improvement of 1.3%, to characterize both our Slow and Moderate trajectories. Our Slow case assumes cost improvements at one-half that rate (0.65%), and our Moderate Advancement case assumes the full 1.3%. The Rapid Advancement case for commercial ASHP, as do other technologies, mimics the scenario adopted in the IEA technology roadmap (IEA 2011); cost is reduced by approximately 40%, which is equivalent to an average rate of improvement of 1.5%.

As we do with ASHPs for residential space heating, we develop efficiency trajectories for both moderate/warm climate ASHPs and cold climate ASHPs to account for the decreased performance of commercial ASHPs in cold climates. For moderate/warm climate ASHPs, the Slow Advancement case assumes broad commercialization of the currently available highest efficiency system, such that by 2050 a typical system adopted has a coefficient of performance (COP) of 3.7. Our Moderate and Rapid Advancement projections are based on low- and high-range targets from the IEA technology roadmap (IEA 2011). Under the Moderate case, we assume that use of variable or multi-stage compressors, and advances in refrigerants and refrigerant management improves the efficiency of typical units to a COP of 4.2 by 2050, which is 30% greater than the starting efficiency. Under the Rapid Advancement case, we assume that technology improvements are achieved more quickly and that additional breakthroughs with non-vapor compression technologies allow efficiencies to climb to a COP of 5.0, which is equivalent to an almost 40% increase relative to the starting efficiency.

Efficiency projections for commercial ccASHPs are based on the assumed timing of achievement of the performance targets identified by the DOE BTO (DOE 2014c), which identify a COP of 2.5 at -25°F and a maximum decrease in peak capacity of 25%. R&D efforts using variable speed, high-efficiency compressors have achieved COPS nearing 2.0 at conditions down to -30°F (Mahmoud 2016; Verma 2017). For the Slow Advancement case, we assume R&D efforts are successful in meeting the DOE BTO target but not until 2040. For the Moderate and Rapid cases, we assume achievement of the DOE BTO target by 2030 and 2020 respectively, with continued improvement until the COPs reach the DOE BTO target of 3.0 identified for residential ccASHP.

Commercial Water Heating

Water heating, despite accounting for only 7% of total energy consumption in the commercial sector (CBECS 2012), is responsible for the second-largest share of fossil energy consumption in the sector (18% or .425 quads). Furthermore, unlike water heating in the residential sector, water heating in the commercial sector is almost entirely fossil-fueled. Eighty-four percent of energy consumed for commercial water heating is either natural gas or fuel oil, with district heat and electricity making up 11% and 5% respectively. Such figures represent a substantial opportunity to electrify commercial water heating by adopting and using HPWHs.

To date, commercial HPWHs have not been deployed in substantial quantities because of their high cost, but they are being used in some commercial laundries, hotels, and restaurants—all facilities that have simultaneous demands for hot water and space cooling. HPWHs output both hot water and cool air, and they can therefore be used simultaneously for water heating and space cooling which can substantially offset their higher capital costs relative to a single function natural gas or an oil-fueled unit.[61] Given their limited deployment to date, little data exist in the literature on their cost and performance. In fact, in its development of standards for commercial water heating, DOE excluded commercial HPWHs, citing a lack of evidence of any standalone HPWHs being adopted (DOE 2016c). Add-on units that operate in tandem with a conventional gas or electric fired boiler are more commonly adopted to improve the overall efficiency of water heating.

As a result of the limited data availability, the Low, Moderate, and Rapid Advancement cases (Figure 23) are based solely on the technology improvement targets outlined in the IEA technology roadmap (IEA 2011) and starting values are taken from the EnergyPATHWAYS default technology assumptions. Future installed costs in the Moderate Advancement and Rapid Advancement cases follow the low and high range cost targets from the IEA technology roadmap (IEA 2011), which idetnify targets of 30% and 40% reductions in cost. Under the Slow Advancement case, we assume costs improve at half the rate of the Moderate Advancement case, resulting in a 15% reduction in cost by 2050. Future efficiency improvements also leverage the IEA technology roadmap targets. Under the Slow case, improvements in commericial HPWH

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[61] Heat pump water heaters output both hot water and cool air, and they can therefore be used simultaneously for water heating and space cooling.

lead to efficiency leveling off at an EF of 3.0, which is equivalent to the mid-range efficiency currently available in the residential market. Efficiencies in the Moderate and Rapid case are assumed to achieve 40% and 60% improvements relative to current levels, which are equivalent to the low and high range of targets from (IEA 2011).

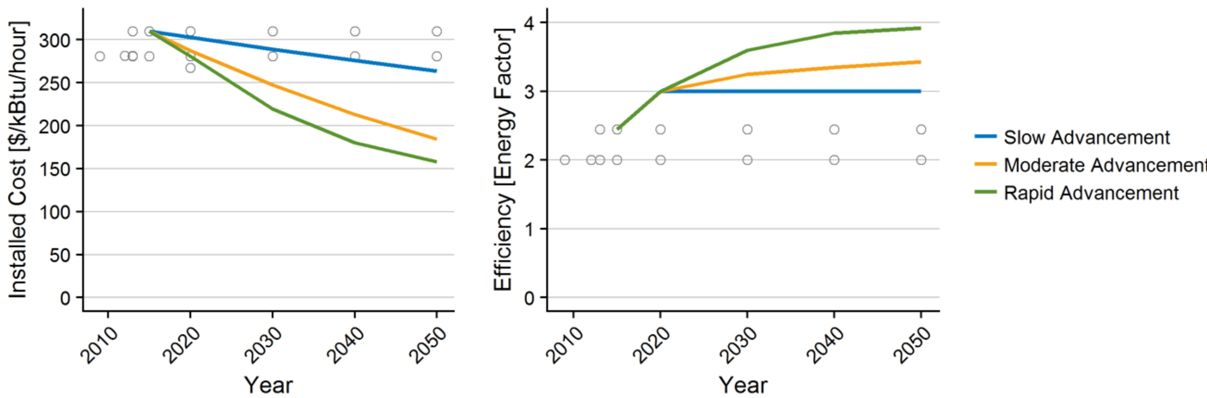

Figure 23. Installed costs (left) and performance projections (right) for commercial HPWHs

Installed costs include both capital and installation costs.

3.2 Levelized Costs

Heat pumps have substantially higher upfront costs than incumbent natural gas and electric resistance technologies, but the higher capital costs are generally offset by lower operating costs that result from the high efficiency of heat pumps. Whether heat pump technologies exhibit economic or total lifetime cost advantages over incumbent technologies depends on the differences in upfront capital and operating costs, which in turn depend on the technologies' efficiencies, operating lifetimes, and fuel costs. To enable direct comparison of the current and future cost and performance of alternative buildings technologies, we develop a set of levelized costs of service (LCOS) metrics for residential and commercial space and water heating technologies. The core components of the LCOS include the capital cost, efficiency, and lifetime of a technology, fuel and maintenance costs, as well as the discount rate associated with the individual adopter, and an assumed usage pattern or capacity factor. The LCOS for each end use technology represents the cost per unit of service delivered over the lifetime of the technology. For space heating and water heating the LCOS is expressed in units of dollars per million British thermal unit (MMBtu) of delivered heat. For space heating, this represents the actual heat delivered to the building, but it does not account for losses associated with distribution of the heat (e.g., through ducting or through the building envelope), and for water heating, this represents the amount of heat delivered to (or absorbed by) the water. Because ASHP technologies can provide both space heating and cooling services, we only associate 50% of the installed cost of ASHPs (and ccASHPs) to the heating service—assuming that approximately half of the capital cost is associated with the cooling application. Fuel prices, electricity prices, maintenance costs, and technology lifetimes are all derived from the AEO 2017 Reference case (EIA 2017a).62 In keeping with our focus on end use, the analysis presented in the main body of

[62] National average fuel prices and electricity prices the AEO 2017 are used.

this report uses a 10% discount rate, which is higher than the 3% or 7% often used as a societal discount rate. Details of the LCOS calculations for building technologies, as well as sensitivities to the discount rate chosen are shown in Appendix A.

We compare the evolution of the LCOSs for the suite of heat pump technologies to that of a set of reference technologies. Each of the reference technologies chosen for comparison currently holds the largest market share for space heating and water heating in the residential and commercial sectors; these reference technologies are gas furnaces[63] and gas-fired storage water heaters respectively. As an additional point of reference, we also calculate the LCOSs for electric resistance space heating (baseboard radiators) and electric resistance storage water heaters.

Figure 24 shows the LCOS for heat pump, gas-fired, and electric resistance technologies by end use and cost component (capital, fuel, and maintenance) for the year 2020. The figure demonstrates a few important points. First, for more-efficient technologies—both electric heat pumps and high-efficiency gas technologies—capital costs make up a larger portion of the levelized costs, but these increased costs are offset by long-run fuel savings. As a result, the fuel costs for higher efficiency technologies make up a smaller portion of the LCOS. This is particularly evident for commercial technologies. Second, relative to electric resistance technologies, heat pumps for space and water heating in both the residential and commercial sector show a cost of service advantage. In other words, if electricity is being used to fuel space and water heating, the high upfront cost of heat pumps is more than offset by savings in electricity costs, when compared to traditional resistance based technologies. Third, the figure demonstrates that at current (or near future expected) cost and performance, residential ASHPs and HPWHs are approaching cost parity with incumbent natural gas technologies in moderate to warm climates, but in cold climates, incumbent gas technologies continue to exhibit an advantage relative to ccASHP. As a result, with modest improvements in the cost and performance of ASHPs, adoption of ASHPs over natural gas technologies could be driven by pure cost advantages in moderate to warm climates but greater improvements would likely be needed for adoption in cold climates. However, this observation—based on national average annual natural gas prices—may not apply in regions with above average natural gas prices (e.g., the Northeast), or over months or in seasons with higher gas prices that would make LCOSs for ccASHPs much more favorable.

[63] For the commercial sector, gas furnaces together with gas-fired packaged heating units are the primary heat source for the largest share of commercial building space (CBECS 2012).

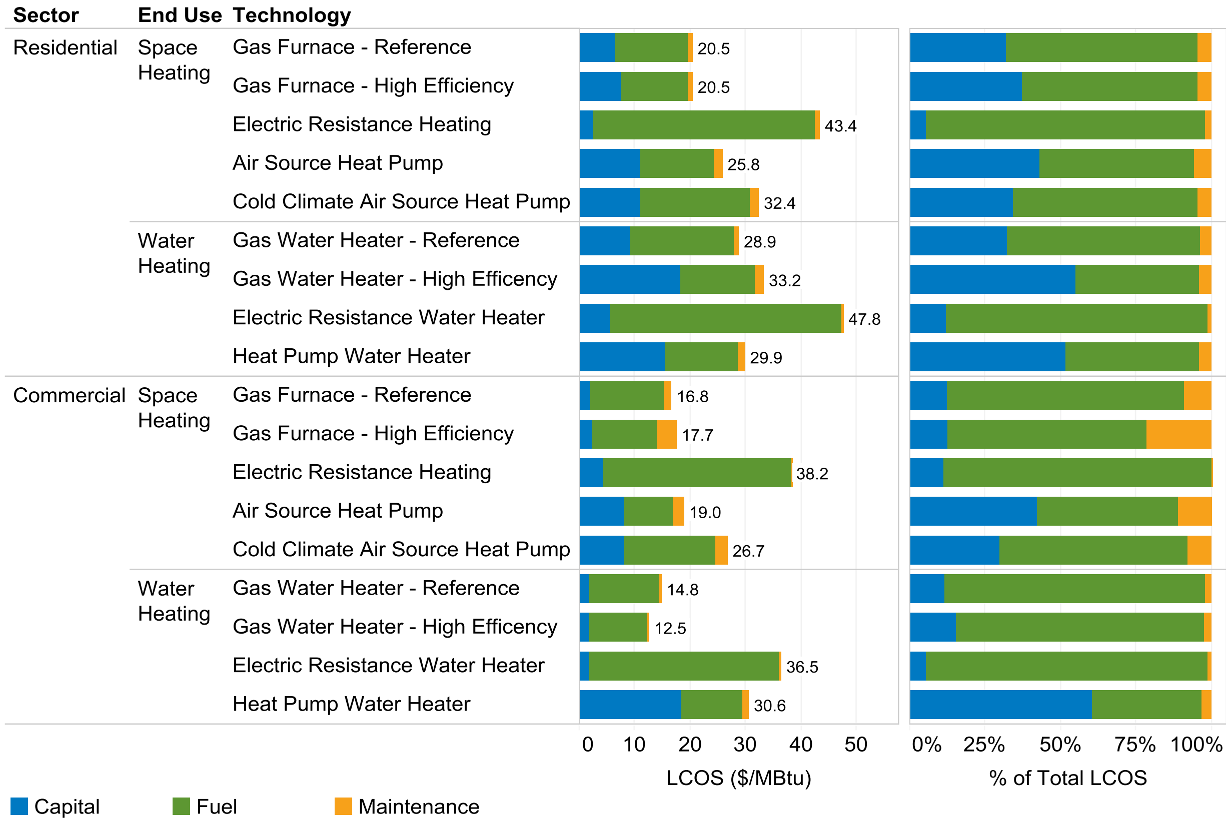

Figure 24. LCOS and percent of total LCOS by cost component in 2020 for the Moderate Advancement case

Third, Figure 24 demonstrates that commercial heat pump technologies, based on the cost and performance assessments described above, are substantially less competitive than their residential counterparts. This relationship is driven by the low capital cost of incumbent gas technologies as well as the current (and projected future) availability of low-cost natural gas. The installed cost of commercial gas furnaces can be as low as $9/kBtu/hour, which is well below the 2020 projected installed cost for commercial ASHPs of $80/kBtu/hour, even if you only associate one-half of the capital cost with heating. On the fuel cost side, Figure 24 demonstrates that despite the substantially higher efficiencies of heat pump technologies, fuel costs make up 50% or more of the total levelized cost of service (with the exception of commercial heat pump water heaters). This is because the cost of electricity on a per unit energy basis is significantly higher than that of natural gas. Price forecasts from the AEO 2017 Reference case show that the delivered electricity price on average from 2020 to 2050 is 3.2 and is 3.0 times greater than that of natural gas for the residential and commercial sectors respectively. This means heat pumps technologies need to be at least 3.4 times more efficient than natural gas technologies to even break even on fuel costs.

Figure 25 shows the evolution of the LCOS of heat pumps for residential and commercial space and water heating in comparison to that of natural gas furnaces, natural gas-fired water heaters, electric resistance heating, and electric resistance storage water heaters. For the two residential end uses, the LCOSs based on the cost and performance projections demonstrate that even with moderate near- to mid-term improvements, ASHPs and HPWHs could achieve cost parity with existing technologies by the beginning to end of the next decade, and with continued improvements could become substantially lower cost in the 2040–2050 timeframe.

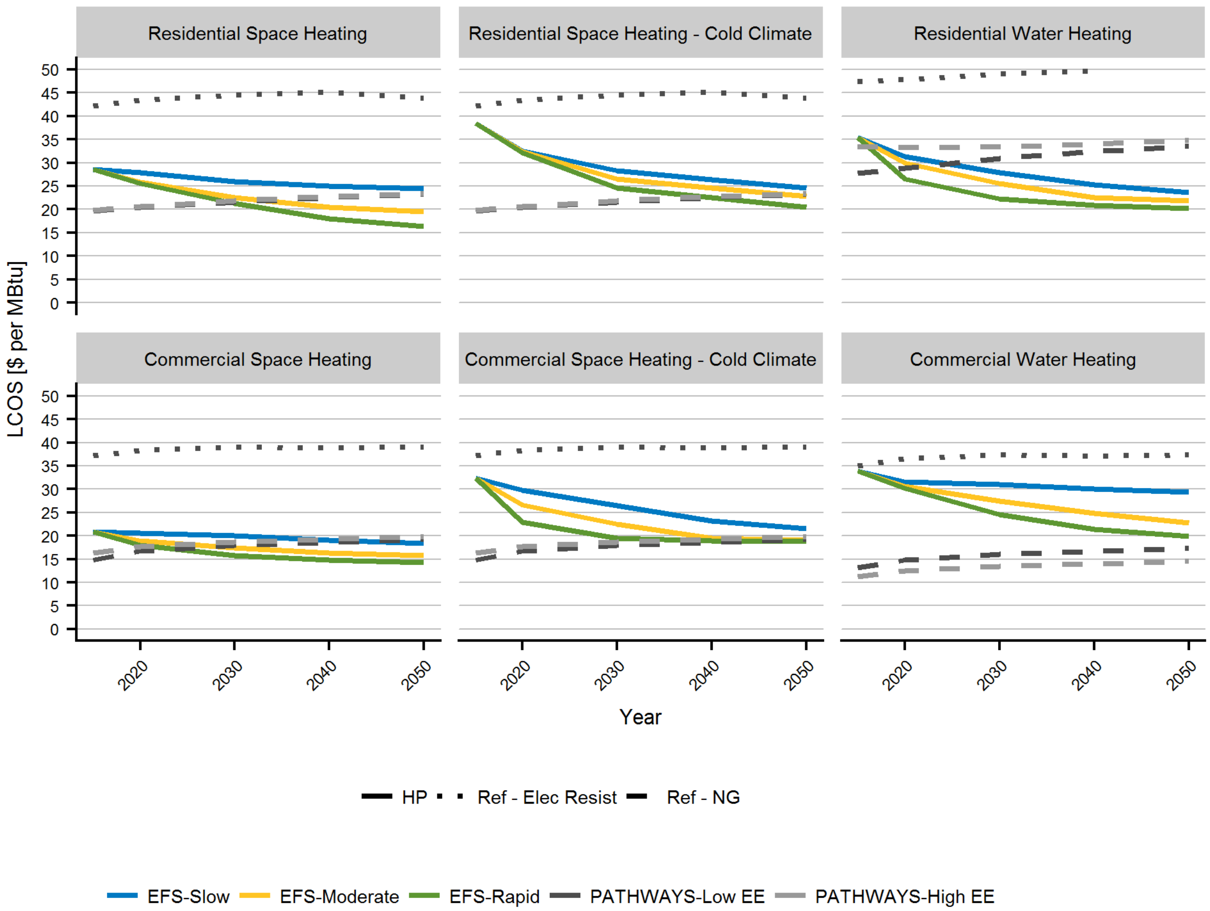

Figure 25. The evolution of the LCOS from heat pumps and natural gas-fired reference technologies for residential and commercial space and water heating

In the commercial sector, heat pump technologies for space heating applications in warm or moderate climates can become cost-competitive by the end of 2040 with only limited improvement and within the next 10 years with faster improvements. In contrast, commercial ccASHP require substantial improvements to achieve cost parity with incumbent gas technologies, but with advancement in the range of the Moderate Advancement or Rapid Advancement cases could do so over the next two decades. For commercial water heating, even under our Rapid Advancement case, cost parity is not achieved. A cost-driven shift in adoption from gas-fired to heat pump water heating in the commercial sector would require cost and performance improvements that, in aggregate, lead to a reduction in levelized cost of over 50%. However, the LCOSs shown for commercial HPWHs are associated with 100% of the capital cost with the heating service. As mentioned above, many applications of commercial HPWHs include use of both water heating and space cooling (the latter of which is a by-product of space heating). If a portion of the capital cost is assumed to be associated with the cooling end use, the LCOS of water heating from HPWHs would be substantially reduced. Again, these LCOSs are calculated based on national average fuel prices, typical demand patterns, and operating conditions. LCOSs of heat pumps for commercial applications could be more favorable in regions (or seasons) with higher natural gas prices or under applications in which they are used at a much higher capacity factor. Furthermore, the technology advancement projections we examined may not bound the full range of potential improvements of heat pumps that could be achieved in the future.

The LCOSs shown above demonstrate that with only modest improvements in cost and performance, residential and commercial heat pump technologies could achieve cost parity with incumbent technologies. Cost parity would likely result in substantial increases in adoption. Of course, cost parity is not the sole determinant of adoption, and other beneficial attributes of heat pumps could induce increased their uptake, including their dual functionality (both heating and cooling services), superior safety relative to combustion based technologies, and increased controllability, while additional barriers to adoption, such as lack of customer awareness and installer knowledge of heat pump systems, and split-incentive or landlord-tenant problems could limit adoption even with achievement of cost parity.

4 Industry

The industrial sector accounts for the second-largest share (32%) of primary energy consumption in the United States (31 quads in 2015). Its electrification share falls between buildings and transportation, with 10 quads (24%) of its primary energy from electricity. Besides electricity, industrial energy uses rely on a mix of fossil fuels and biomass (EIA 2017a).

As shown in Figure 26, process heating, combined heat and power and/or cogeneration process, and conventional boiler use account for significant portions of final energy use in manufacturing.[64] Approximately 5.8 quads of natural gas and 0.78 quads of coal were used directly by manufacturing industries in 2014, with most occurring in process heating, combined heat and power, and/or cogeneration, and conventional boilers. Byproducts (e.g., blast furnace gas, petroleum coke, and black liquor) comprised nearly 30% of final fuel energy use in 2014, but they were not identified by end use by EIA.[65]

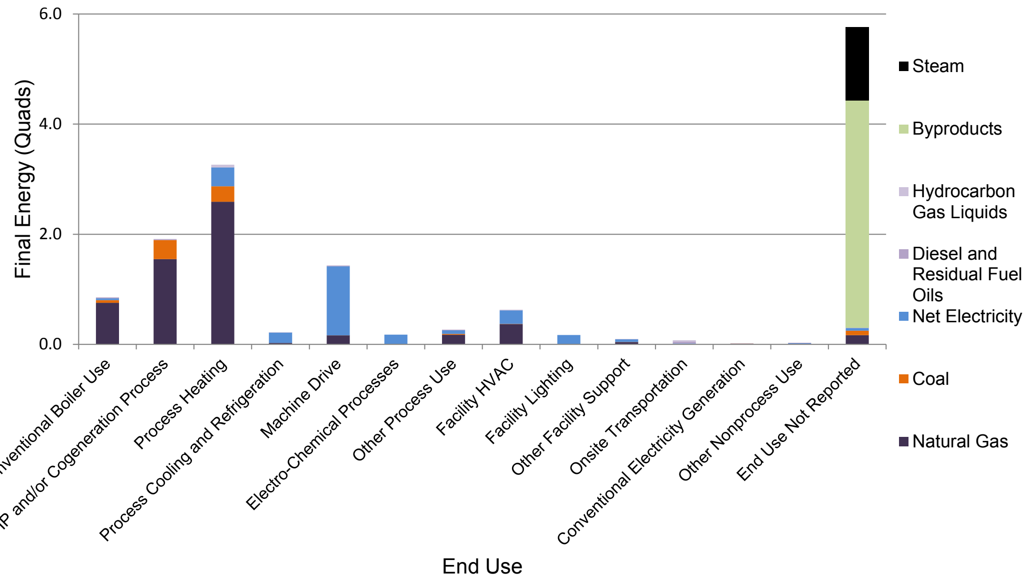

Figure 26. Final fuel energy use in manufacturing by end use and fuel type: 2014 Manufacturing Energy Consumption Survey

Figure does not include feedstock energy use (approximately 5.3 quads in 2014).
Data are from EIA (2017b)

[64] EIA conducts an energy consumption survey only for manufacturing industries. Analogous detail is not available for the agriculture, mining, and construction industries.
[65] Byproducts are typically allocated to the conventional boilers, combined heat and power, and process heating end uses. See DOE (2014) and Fox, Sutter, and Tester (2011).

For this analysis, we consider electrification in the industrial sector for the following subsectors: agriculture, food, glass and glass products, chemicals, primary metals, transportation equipment, plastic products, other wood products and printing and related support, and other manufacturing. Additionally, electrification of heating, ventilation, and air conditioning (HVAC) and machine-drive end uses is assumed for all agriculture and manufacturing subsectors. Electrification in other industry subsectors and end uses (e.g., pulp and paper, mining, construction, computer and electronic products) may be possible but is not presented here because of their reliance on process byproducts for combustion fuels, their relatively minor historical energy use, or the relatively limited literature available (within the already sparse set of studies devoted to industry electrification writ large). Indirect electrification (e.g., power-to-gas and power-to-liquids) is not considered at this time for the industrial sector. See Lechtenböhmer et al. (2016) as an example analysis of direct and indirect electrification potential for industry. The industrial subsectors and end uses considered for electrification are summarized in Table 12. The table includes the electricity fraction of site fuel energy use in 2014.

The current state of published research for industrial electrification does not support a level of analytic detail that is comparable to the buildings and transportation sectors. Assessing technology advancement possibilities for electrification technologies, termed "electrotechnologies" in industry, for the industrial subsector is challenging, perhaps more so than for the transportation and buildings sectors, because of the diversity of end uses and technologies and the very limited available data and research on the topic. One purpose of this report is to call attention to the extent of these research gaps by constructing analysis around what little information we found. A much more detailed and thorough analysis of industrial electrification would be a significant contribution to the literature.

As a consequence of the very limited available data and research, this section differs in structure and content from Sections 2 and 3. In particular, we do not include cost projections; instead, energy efficiency projections are used as proxies for cost trends. We first summarize the recent literature for industrial electrification and identify the mapping between industrial subsectors, end uses, and electrotechnologies. This mapping requires more definition than is required in the other sectors. Second, we present two examples of economic analyses of electrotechnologies: one based on the "industrial assessment center" (IAC) database (U.S. DOE EERE Advanced Manufacturing Office 2017) and the other for a natural gas boiler replacement. While these analyses are informative, they do not offer sufficient information to inform cost projections. Finally, similarly to how we present efficiency projections for the other two sectors, we discuss the approach used to develop the projections in aggregate industry efficiency improvement.

Table 12. Industry Subsectors and End Uses Considered for Electrification with Electricity Fraction of Site Fuel Energy Use[a]

	End Use							
Industry Subsector	**Process Heat (Including Boilers)**	**Process Cooling**	**Machine Drive[c]**	**Electro-Chemical Processes**	**Other Process**	**Facility HVAC[c]**	**Facility Lighting**	**Other Facility Non-Process**
Agriculture	nd	nd	nd	nd	nd	nd	nd	nd
Construction	nd	nd	nd	nd	nd	nd	nd	nd
Mining	nd	nd	nd	nd	nd	nd	nd	nd
Food	5%	96%	95%	na	31%	36%	100%	0%
Chemicals	2%	71%	73%	100%	12%	40%	100%	50%
Pulp and paper	7%	100%	89%	100%	69%	32%	100%	na
Glass and glass products	8%	33%	71%	100%	0%	33%	100%	na
Cement and lime	3%	100%	94%	0%	100%	100%	100%	na
Primary metals[b]	25%	55%	91%	100%	14%	28%	100%	50%
Transportation equipment	19%	100%	100%	100%	58%	37%	100%	100%
Plastic and rubber products	41%	100%	99%	100%	na	48%	100%	na
Other wood products	17%	na	100%	100%	100%	50%	100%	na
Printing and related support	9%	100%	96%	100%	100%	42%	100%	na
Other manufacturing[d]	38%	100%	100%	100%	100%	54%	100%	na

[a] Shaded cells indicate the subsector and end use considered for electrification. Electricity fractions do not include on-site combustion generation. Data are from EIA (2017b).

[b] Electrification is only considered for current natural gas process heating in aluminum production.

[c] Machine drives and facility HVAC are modeled as aggregates of industry subsectors. The table therefore indicates a subsector has been identified for electrification even though it may already be completely electrified. Machine drives in the pulp and paper, cement and lime, iron and steel, and aluminum sectors were excluded from analysis due to modeling limitations. Specifically, NEMS uses a process flowsheet method, and it does not separately define the machine-drive end use. See EIA (2014) for a detailed discussion of methods used in the NEMS Industrial Demand Module.

[d] Net electricity fraction representative of miscellaneous manufacturing (NAICS 339)

nd = no data

na = not applicable; no numerical value in Manufacturing Energy Consumption Survey

4.1 Summary of Literature

Limited literature identifies the industrial subsectors and their end uses that could be expected to undergo additional electrification in the future, as well as the types of electrotechnologies. The paucity of the literature indicates new research is needed to develop an understanding of industrial electrotechnologies and industrial electrification in detail that is comparable to that of the transportation and buildings sectors. Nonetheless, the existing literature, along with expert opinion and approximate economic calculations, enables us to develop an initial understanding of electrotechnologies and opportunities.

The three sources we identified and use as the basis for selecting the industries and electrotechnologies relevant to this analysis are Dennis (2016), Cheremisinoff (1996), and CEA Technologies, Inc. (2016). The identification and mapping of electrotechnologies and their industrial applications are generally consistent across these three sources. However, none of the sources provide a detailed discussion of the factors that were considered, or overall methodology used, in identifying and matching relevant industries and electrotechnologies. Table 13 summarizes our identification of relevant industries and electrotechnologies based on these three sources. We excluded emerging, disruptive, and other technologies that have yet to be commercialized. Obtaining relevant technical cost and performance data for these electrotechnologies would likely be even more difficult than for commercialized electrotechnologies.

Table 13. Industrial Subsectors and End Uses Relevant to Electrification Scenarios

Industrial Subsector	End Use	Representative Electrotechnology
All manufacturing industries and agriculture	Building HVAC	Industrial heat pump
	Machine drive	Electric machine drive
Food, chemicals, transportation equipment, plastics, and other manufacturing	Process heat	Electric boiler
Food	Process heat	Industrial heat pump
Chemicals	Process heat	Resistance heating
		Industrial heat pump
Glass and glass products	Process heat	Direct resistance melting (electric glass melt furnace)
Primary metals	Process heat	Induction furnace
Transportation equipment	Process heat	Induction furnace
Plastic and rubber products	Process heat	Resistance heating
	Process heat	Infrared processing
Other manufacturing	Process heat	Resistance heating
Other wood products and printing and related support	Process heat: curing	Ultraviolet curing

Dennis (2016) identifies the top ten industrial growth areas for electrotechnologies. Of these, cryogenics, direct arc melting, and induction heating comprise over 50% of the 20.8 billion kWh of electricity consumption growth projected for 2015 to 2020. However, it is unclear whether this growth represents relative growth of electricity consumption through substitution for combustion technologies, absolute increase in energy use for relevant industrial sectors, or both. The factors identified for these electrotechnologies—industrial sector growth, product quality, and productivity—represent absolute and relative (i.e., substitution of electrotechnologies for combustion technologies) growth, and it is not possible to distinguish the effects of the two sources of electricity consumption growth.

4.2 Economic Analysis of Electrotechnologies in Industry

Very little publicly available cost data for industrial electrotechnologies exist. Of the available data, many are anecdotal. Although some data are available for certain industries, end uses, and technologies, the lack of consistent metrics limits their use for developing projections.[66] In the absence of consistent and systematic economic analysis of electrotechnology adoption in industry, we develop two separate economic analyses.

First, we use data from the DOE IAC database (U.S. DOE EERE Advanced Manufacturing Office 2017) to conduct a high-level analysis of electrification recommendations and adoption. However, our analysis of IAC data that compared payback period and adoption of electrotechnologies is ultimately inconclusive, meaning that the length of payback appears to be uncorrelated with whether a recommended electrotechnology is adopted. Second, we compare capital and fuel costs between electric and natural gas-fired boilers. The comparison of boilers shows that although the electric boiler has a lower capital cost and is more energy efficient, electricity is roughly three times as expensive as natural gas on an energy basis.

4.2.1 Payback Analysis

The Departments of Energy's IACs provide no-cost assessments to small and medium-sized U.S. manufacturers for energy, productivity, and waste improvements (U.S. DOE EERE Advanced Manufacturing Office n.d.). Because large facilities are ineligible to participate in the IAC program, opportunities specific to large facilities are not included in the data. Data from 17,872 assessments and 135,560 recommendations dating from 1981 are available for download (U.S. DOE EERE Advanced Manufacturing Office n.d.).

In a typical assessment, an IAC team sends the client a pre-assessment form to collect information related to industry type, production schedule, historical utility bills, and the inventory of major energy-using equipment. After a pre-assessment analysis of the client's operations, which includes possible energy savings recommendations, the IAC conducts an on-site assessment. Post assessment activities involve compiling an IAC report that describes individual energy savings recommendations. Follow-up activities are conducted within six to nine months of the client receiving the report to track recommendation implementation status

[66] See Cheremisinoff (1996) and CEA Technologies, Inc. (2016). Examples provided of typical costs include 60–70 dollars per kilowatt (kW) for 60-cycle coreless induction furnaces and $250,000 for a furnace requiring 2,000 kW at 1 kilohertz to heat six tons per hour of high volume 3.5-inch bars for forging (Cheremisinoff 1996).

and then upload final data to the IAC database (U.S. DOE EERE Advanced Manufacturing Office 2017a).

Fuel switching recommendations that are of interest for analyzing the potential for electrifying industrial energy end uses are among the energy savings recommendations made in IAC assessments. The seven standardized recommendations that were identified as relevant to electrification are summarized in Table 14. Although most do not reference specific types of equipment or the particular industrial process to which they apply, we nonetheless use these recommendations for economic analysis, given the general lack of data for the industrial sector.

Table 14. IAC Assessment Recommendations Relevant to Industrial Electrification

Assessment Recommendation Code (ARC)	Description
2.1321	Replace fossil fuel equipment with electrical equipment
2.1322	Use electric heat in place of fossil fuel heating system
2.1323	Replace gas-fired absorption air conditioners with electric units
2.2221	Use immersion heating in tanks, melting pots, etc.
2.2222	Convert liquid heaters from underfiring to immersion or submersion heating
2.4324	Replace hydraulic / pneumatic equipment with electrical equipment
2.5113	Use direct flame impingement or infrared processing for chamber type heating

The IAC database contains information on the implementation cost, simple payback, and implementation status for each recommendation. We aggregate the data by industrial subsector to roughly analyze the adoption of electrotechnologies. The mean implementation cost and simple payback are summarized in Table 15. The values for each recommendation reflect the heterogeneity of processes and other characteristics of each industrial subsector. However, with the exception of using heat pumps for space conditioning and using direct flame impingement or infrared processing, most recommendations have a simple payback of three years or less.

Table 16 summarizes the implementation rates—defined as the percent of total recommendations reported as either implemented or pending by assessment recommendation code—for electrification-relevant recommendations by industrial subsector. Based on these data, no subsector or recommendation is consistently implemented. For example, the implementation rate for the recommendation to replace fossil fuel equipment with electrical equipment ranges from 0% to 100%. The fabricated metal products subsector, which received the most electrification-relevant recommendations, has an implementation rate of 0% to 40%. Recommendations may have been implemented after the assessment survey, but no additional surveys of participants were conducted beyond the initial nine-month period.

Table 15. Summary of Electrification-Relevant IAC Recommendations[a]

Subsector	Implementation Cost Range ($000) | Simple Payback Range (Years)													
	Use Immersion Heating in Tanks, Melting Pots, etc.		**Convert Liquid Heaters from Underfiring to Immersion or Submersion Heating**		**Replace Fossil Fuel Equipment with Electrical Equipment**		**Use Electric Heat in Place of Fossil Fuel Heating System**		**Replace Hydraulic/ Pneumatic Equipment with Electrical Equipment**		**Replace Gas-Fired Absorption Air Conditioners with Electric Units**		**Use Heat Pump for Space Conditioning**	
	Cost ($000)	**Payback (Years)**	**Cost ($000)**	**Payback (Years)**	**Cost ($000)**	**Payback (Years)**	**Cost ($000)**	**Payback (Years)**	**Cost ($000)**	**Paybac k (Years)**	**Cost ($000)**	**Payback (Years)**	**Cost ($000)**	**Payback (Years)**
Agriculture	—	—	1	2	—	—	—	—	26–69	—	—	—	—	—
Food	0.1–80	<1–3	0.8–14	1–4	0.001–77	<1–1	—	—	0.4–326	<1–6	—	—	4–22	<1–5
Textile mills	—	—	—	—	40–144	1	—	—	2	2	—	—	—	—
Lumber and wood products	—	—	—	—	1–17	<1–3	—	—	0.2–242	<1–2	—	—	11	—
Paper	—	—	—	—	6–68	<1–5	3–80	<1–2	0.8–23	<1–4	—	—	—	—
Printing	0.02	<1	—	—	5	4	—	—	4–19	<1–2	—	—	2–68	1–4
Chemicals	25	2	—	—	2–31	<1–5	0.7–5	<1	0.9–32	3–8	—	—	—	—
Petroleum refining	—	—	—	—	2–963	<1–3	—	—	1–80	3–4	—	—	—	—
Rubber and plastics	1–66	<1–2	—	—	0.7–50	<1–3	—	—	0.07–252	<1–5	3	5	0.7–1,293	<1–2
Stone, clay, glass, and concrete	—	—	4	—	2–6	<1–1	2–6	<1–2	1–18	<1–2	—	—	6	3
Primary metals	—	—	—	—	10–2,000	<1–6	6–190	<1–4	0.2–110	<1–3	—	—	—	—
Fabricated metal products	1–55	<1–2	12	<1	0.8–150	<1–5	2–146	<1–3	0.7–92	<1–5	—	—	1–429	4–25
Machinery and computer equipment	1	1	2	<1	0.3–55	<1–5	0.6–1	<1–2	0.2–27	<1–3	—	—	10–335	2–4
Electronic and other electrical equipment	—	—	0.8–37	4–6	0.2–161	<1–2	325	3	1–25	1–4	—	—	7–152	6
Transportation equipment	26–38	2–5	—	—	0.6–100	<1–3	2	—	0.9–14	<1–1	—	—	10–96	3–7
Miscellaneous manufacturing	—	—	—	—	11–384	<1	—	—	0.5	<1	138	3	182	5
Recommendation Average	**50**	**2**	**11**	**3**	**84**	**2**	**38**	**1**	**24**	**2**	**71**	**4**	**128**	**5**

[a] Analysis of data from U.S. DOE EERE Advanced Manufacturing Office (2017)

Table 16. Implementation Rates (%) (Implemented and Pending) for Electrification-Relevant IAC Recommendations[a]

Subsector	Use Immersion Heating in Tanks, Melting Pots, etc.	Convert Liquid Heaters from Underfiring to Immersion or Submersion Heating	Replace Fossil Fuel Equipment with Electrical Equipment	Use Electric Heat in Place of Fossil Fuel Heating System	Replace Hydraulic/ Pneumatic Equipment with Electrical Equipment	Replace Gas-Fired Absorption Air Conditioners with Electrical Units	Use Heat Pump for Space Conditioning	Number of Recommendations with Reported Implementation Status
Agriculture	—	0	—	—	50	—	—	3
Food	25	100	57	—	32	—	0	35
Textile mills	—	—	0	—	0	—	—	3
Lumber and wood products	—	0	40	—	14	—	100	20
Paper	—	—	67	0	56	—	—	18
Printing	0	—	100	—	40	—	40	12
Chemicals	0	—	20	67	43	—	—	16
Petroleum refining	—	—	0	—	0	—	—	5
Rubber and plastics	33	—	33	—	25	0	20	24
Stone, clay, glass, and concrete	—	0	50	0	75	—	0	12
Primary metals	—	—	33	0	33	—	—	18
Fabricated metal products	20	0	25	20	40	—	0	42
Machinery and computer equipment	0	100	0	67	25	—	25	27
Electronic and other electrical equipment	—	50	40	0	0	—	33	17
Transportation equipment	0	—	0	100	40	—	67	17
Miscellaneous manufacturing	—	—	0	—	0	100	100	4
Number of Recommendations with Reported Implementation Status	**17**	**8**	**69**	**21**	**128**	**1**	**29**	**273**

[a] Analysis of data from U.S. DOE EERE Advanced Manufacturing Office (2017)

One might expect that recommendations with shorter payback times (typically less than two years) might be implemented more often than recommendations that have longer payback times. Figure 27 plots implementation rate against average simple payback time for the electrification-relevant IAC recommendations shown in Tables 15 and 16.[67] Visual inspection of the figure indicates there is virtually no correlation between the average payback period and the implementation rate for a recommendation.[68] Even recommendations with a payback of less than one year have an implementation rate that varies from 0% to 100%.

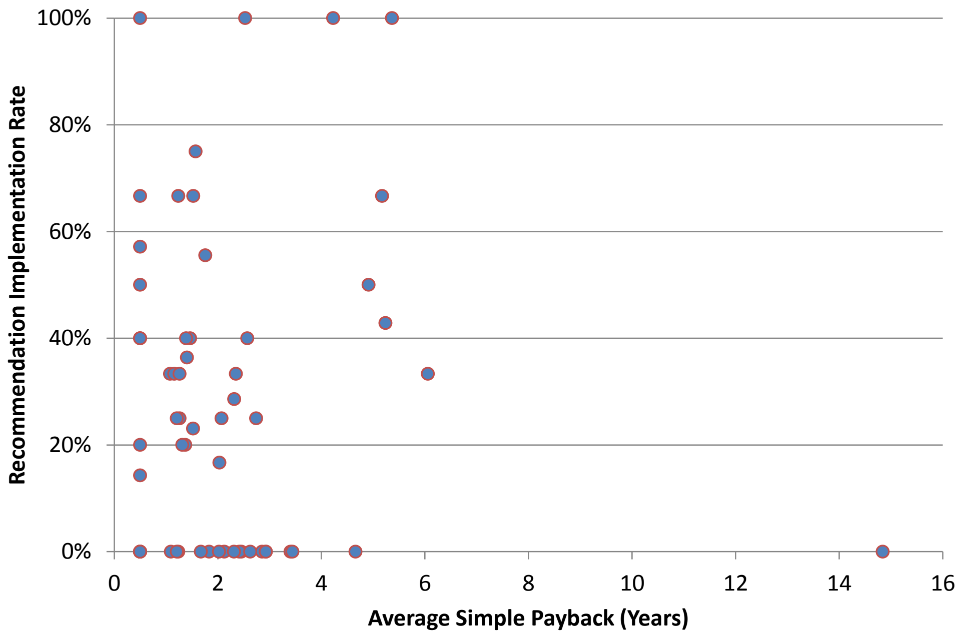

Figure 27. Comparison of simple payback and implementation rate for electrification-relevant IAC recommendations

The implementation rate includes recommendations with pending implementation.
Recommendations with payback of less than one year are shown with a payback of 0.5 year.

IAC assessment data have been used in several studies of energy efficiency measure adoption in industry. Anderson and Newell (2004) found that firms respond more to implementation costs than to energy savings and that a 10% increase in payback time is associated with a 0.8% decrease in the probability of recommendation adoption. Anderson and Newell also observe that their results are robust to alternate model specifications that include the type of industry (i.e., Standard Industrial Classification [SIC] code), plant size, and assessment year. Muthulingam et al. (2013) found that from 1981 to 2006 more than 50% of the IAC energy savings recommendations were not implemented and that the implementation rate was decreasing over time. Abadie, Ortiz, and Galarraga (2012) identified implementation rates by SIC code and found that participants in the primary metals and petroleum and coal products industries had the lowest and highest implementation rates respectively. Abadie, Ortiz, and Galarraga also found that energy management recommendations associated with natural gas use had lower than average probability of implementation. Most recently, Dalzell, Boyd, and Reiter (2017) linked IAC data

[67] Not all recommendations included implementation status and payback period.
[68] Pearson correlation coefficient equal to 0.028.

with confidential facility-level data from the U.S. Census of Manufacturers and observed facilities that received IAC assessments in 2007 were less energy-efficient than peers not receiving assessments. Dalzell, Boyd, and Reiter found that this discrepancy disappeared in 2012, which suggests that assessments improved the energy efficiency of the participating facilities.

Electrification-relevant IAC recommendations are a subset of the energy management recommendations analyzed by the referenced studies, but they were not addressed separately in any of the published results. Analysis of electrification-related recommendations commensurate with these studies (e.g., developing a logit model of recommendation adoption) is outside the scope of this report. Most of the IAC recommendation categories, however, do not provide information about specific technologies. Consequently, results of a greatly expanded analysis of electrification-related recommendations are unlikely to be used to model the adoption of individual electrotechnologies within particular industries. Nonetheless, it is still possible to draw general conclusions that are relevant to electrotechnologies from this body of research on energy efficiency adoption. Although facilities do respond to financial measures of new equipment adoption (e.g., payback, cost, savings, and energy prices), these measures do not completely explain the adoption decision. Anderson and Newell (2004) examined the reasons provided for not adopting recommendations and found that as much as 82% of the reasons could be due to institutional factors (e.g., aversion to process or equipment changes for non-economic reasons) and as much as 58% of the reasons could be due to financing (e.g., limited cash flow).[69]

Non-energy benefits, such as improved productivity and product quality have been identified as important features for certain electrotechnologies (Allen Dennis 2016; CEA Technologies, Inc. 2016.; Cheremisinoff 1996). Non-energy benefits were likely not included in IAC payback calculations; including these benefits would decrease electrotechnology payback time.

Without more information on the types of equipment and processes associated with the recommendations, as well as the capital investment decision-making process for each facility, the IAC database has limited use for informing future industrial electrification scenarios. The next section presents a comparison of the capital and operating costs of natural gas-fired and electric boilers as an additional assessment example of industrial electrification.

[69] Because of confidentiality concerns, the publicly available version of the IAC database does not currently provide rejection reasons.

4.2.2 Equipment Fuel Cost Analysis

Although the IAC database provides electrification recommendation information for small and medium enterprises across a wide range of industries, the database has limited detail on processes and equipment for those industries. We perform the following economic analysis of natural gas and electric boilers as a generally relevant example of switching from equipment with fuel-fired burners to an electrotechnology based solely on capital and fuel costs.[70] This rough analysis includes only capital and operating costs, and it excludes several types of costs that may be important considerations—such as installation and maintenance costs, and differences in boiler lifetime—because of a lack of data.

List purchase prices are assumed to equal capital costs, which we obtained from Lattner Boiler Company (2015). The natural gas boiler is assumed to operate at 80% efficiency, and the electric boiler is assumed to operate at 100% efficiency in converting electricity to heat. Operating costs only include fuel costs of electricity and natural gas. Fuel costs are analyzed by Census Region and are calculated as the state consumption-weighted average electricity and natural gas prices in 2015 for industrial customers reported by the EIA (2017c, 2017b, 2017d).

On average, the capital cost of an electric boiler is nearly 40% less than that of an equivalent natural gas-fired boiler. However, regional electricity prices are at least three times natural gas prices on an energy content basis (per MMBtu)[71] When accounting for the relative efficiency of each type of boiler, the hourly fuel cost of an electric boiler could be between 2.5 and 3.7 times that of a natural gas boiler. Example capital and fuel costs for 100-boiler horsepower[72] boilers are summarized in Table 17. Whatever capital cost advantage exists with an electric boiler is outweighed by operating costs in less than a year of operation, as indicated by the first-year costs. This analysis was conducted with 2015 natural gas fuel and electricity costs. Because natural gas prices in 2015 were at near-historical low levels[73] and future prices are difficult to predict, the gap between electric and natural gas boilers could narrow from the range indicated here, and lower electricity prices in the future could also reduce any cost differences.[74]

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[70] The natural gas boiler is assumed to be a Scotch marine (i.e., fire-tube) boiler that provides steam at 150 pounds per square inch. The electric steam boiler is assumed to be 480-volt cabinet electric. Prices are available for sizes from 15 to 250 boiler horsepower.

[71] One MMBtu equals 293.07 kilowatt-hours.

[72] One boiler horsepower equals 33,475 Btu/hour.

[73] Nominal industrial electricity and natural gas prices were compared from 1990 to 2015. The smallest spread between the two energy carriers occurred in 2005, when national electricity prices were two times natural gas prices on an MMBtu-basis.

[74] Because natural gas is also used in the electricity sector, higher natural gas prices could lead to higher electricity prices making it even more challenging to close this gap in costs.

Table 17. Capital and Fuel Cost Comparison of 100-Boiler Horsepower Natural Gas and Electric Steam Boilers

Census Region	Electric Boiler				Natural Gas Boiler			
	Purchase Price ($)	Electricity Price ($/MMBtu)	Hourly Fuel Cost ($)	First-Year Cost ($)[a]	Purchase Price ($)	Natural Gas Price ($/MMBtu)	Hourly Fuel Cost, ($)	First-Year Cost ($)[a]
Midwest	53,860	20.35	68.75	416,858	87,540	5.37	22.47	206,190
Northeast		24.47	82.69	490,461		7.87	32.93	261,399
South		17.63	59.55	368,303		3.80	15.91	171,567
West		24.09	81.39	483,615		6.20	25.94	224,501

[a] First-year cost is equal to the sum of purchase price and first year fuel cost. Assumed 5,280 annual operating hours.

4.3 Industry Energy Efficiency Projections

Unlike the buildings and transportation sectors, electrotechnology cost advancement projections were not developed for the industrial sector because we found no literature sources for costs. Projecting electrotechnology energy efficiency improvement was considered as an alternative approach, but this too was not pursued further because we were unable to find relevant literature sources. The exceptions to this are industrial HVAC heat pumps and boilers, where we assume the same energy efficiency as commercial buildings heat pumps and boilers respectively. A much more detailed and thorough analysis of industrial electrification would be a significant contribution to the literature.

Although we were unable to find energy efficiency projections for individual technologies, the technical possibility curves (TPCs) used by NEMS are one source of aggregate industry efficiency projections. TPCs define in NEMS the annual change in unit energy consumption[75] of existing and new capacity and technology bundles relative to a baseline year (2010 for AEO2017). TPCs are derived from assumptions about changes to energy intensity and new technology adoption over time (EIA 2017e). TPCs are not defined for individual technologies; instead, TPCs represent aggregations by end use or major process operation. The types of changes represented by TPCs include incremental energy and process efficiency improvements for existing processes, which is analogous to increasing the balance of plant furnace energy efficiency in ethylene steam cracking (DOE 2015), as well as new energy-efficient process technology, which would capture implementing a "breakthrough" catalyst for styrene monomer production (DOE 2015).

TPCs were used in NEMS to represent earlier availability and higher energy efficiency of more advanced equipment in AEO Technology Side Cases (i.e., the Integrated High Demand Technology Case) until AEO2015 (U.S. Energy Information Administration 2014). These Side Cases also included a fixed-technology case, where new the energy efficiency of new industrial facilities was held constant at the base year level.

[75] Unit energy consumption is the amount of energy used per unit output (e.g., Btu per pound or Btu per dollar value of shipments).

5 Summary

This report presents estimated cost and performance data for electric technologies considered in the Electrification Futures Study (EFS), which is a detailed and comprehensive analysis of the effects of electrification of end-use service demands in all major economic sectors—transportation, residential and commercial buildings, and industry—for the contiguous United States through 2050. This first report in the EFS series supports the EFS analytic goals by establishing technology advancement sensitivity cases that provide a range of values for cost and performance data of end-use electric technologies. The report compiles the sources, assumptions, and uncertainties of the projected technology assumptions in each of the economic sectors. These projections—comprising slow, moderate, and rapid technology advancement sensitivity cases—and their underlying data are the primary result presented in the report.

These projections will be used in future EFS reports to present a range in comparative electricity use and cost across electrification scenarios, highlighting the uncertainty inherent in such values. The adoption scenarios in future EFS reports will not be determined by the costs presented here, as other factors beyond cost will frame those scenarios. These costs can appropriately be used as rough initial approximations for the types of cost, the relative costs among options, and the order of magnitude of costs of end-use electrification. Similarly, by providing a range of sensitivity cases with different costs, we seek to highlight the inherent uncertainties in long-term technology advancement, presenting costs consistent with futures that are qualitatively different with respect to investment in and success of electric technologies.

Methodologies for this work entailed interpretation of the published literature, expert judgment, and extrapolation or interpolation. Literature coverage varies considerably by sector and technology, with considerably less data available to support comprehensive analysis in the industrial sector. Despite this variation, we can summarize these data into projected Slow Advancement, Moderate Advancement, and Rapid Advancement technology sensitivity cases for transportation and buildings sector technologies (Table 18). The Rapid Advancement projections reflect technology cost reductions and performance improvements consistent with favorable public and private decisions leading to technology learning. The Slow Advancement projections follow business-as-usual trajectories for technology learning. The Moderate Advancement projections represent an intermediate pace of learning that does reflect electric technology progress beyond those reflected in a business-as-usual perspective.

Few literature sources offer cost and performance estimates of electrification technologies through 2050. In the *transportation sector*, light-duty vehicles (LDVs) are best represented in the literature; even in that subsector, few independent projections exist. We base our estimates on Moawad et al. (2016), who report Autonomie modeling results for LDVs, and we also apply updated battery costs targets from DOE-VTO. For medium-duty vehicle (MDVs) and heavy-duty vehicle (HDVs), we use analyses from CARB (2015, 2017b, 2017c) and manufacturer specifications from current available models (Proterra 2017; BYD 2017). Because of both scope and literature limitations, we do not explore distinctive vocational applications among MDVs and HDVs that could reveal especially competitive niches. Future work to characterize these opportunities, including their infrastructure requirements would improve the foundational data on electrification of the transportation sector.

In the *buildings sector*, we focus on the technologies with the greatest electrification opportunities, and we use AEO values for the others. The literature for buildings end-use electrification is similar to that of the transportation sector in that it has many gaps with regard to long-term projected cost and performance. Key technical literature leveraged in our analysis includes, the TSDs associated with the development of appliance and equipment efficiency standards (DOE 2009, 2015a, 2016c, 2016d), the DOE BTO Emerging Technology Program "roadmap" reports and associated future cost and performance targets (DOE 2014c, 2014b, 2016b), technical reports associated with ongoing research on individual emerging technologies (Baxter 2017b, 2017b; Gluesenkamp 2016; Mahmoud 2016; Messmer 2015; Shen 2017; Verma 2017), the IEA's Technology Roadmap for Energy Efficient Buildings (IEA 2011), and a large set of reports from research centers, consulting agencies, and industrial associations summarizing costs, performance, and market potentials for heat pump technologies (Roberts et al. 2012; NEEP 2017a, 2017b, 2016, 2014, 2013, 2011; NEEA 2015; Navigant 2015; Groff 2014; Cadmus 2016; Baxter and Groll 2017b; M. Lapsa and Khowailed 2014; Korn, Walczyk, and Jackson 2017). Future work to improve the projections presented here could examine the performance implications and future costs of the substitution of specific heat pump components (e.g., changing compressor types, using non-vapor compression processes, and changes to working fluids). This would enable the development of bottom-up component level projections of future cost and performance, substantially increasing their accuracy.

For the *industrial sector*, the literature on future electric technologies ("electrotechnologies") is insufficient to develop informed and plausible cost and efficiency sensitivity cases. We describe the technical possibility curves (TPCs), which are used in NEMS to define the annual change in unit energy consumption of existing and new capacity and technology bundles relative to a 2010 baseline, as a source of aggregate energy efficiency projections. TPCs are derived from assumptions about changes to energy intensity and new technology adoption over time. We also present examples of two economic analyses of electrotechnologies, one based on IAC data and the other for a natural gas boiler replacement. Future work could fill the numerous gaps in the industrial sector by developing current technology costs, in addition to efficiency and cost projections based on expert judgment or engineering analysis.

Summary charts and tables are included in the report, and supplemental tabular data are available at https://doi.org/10.7799/1414279. Figure 28 summarizes the percentage difference, relative to the Slow Advancement projection for the Moderate Advancement and Rapid Advancement projections by sector, technology, metric, and year. Recall that the Slow Advancement case approximates a business-as-usual trajectory. The figure indicates considerable variation in the spread between Slow Advancement and Rapid Advancement across technologies. Results for transportation and buildings sectors also include the projections for levelized costs for each technology advancement sensitivity, identifying the year of cost equivalence relative to incumbent technologies. Many, but not all technologies reach cost equivalence. Again, we see a range of spread between the projections. The Rapid Advancement projections accelerate cost parity in as little as a few years in some cases and in others make the difference between reaching parity and not reaching cost parity during the study period. As indicated above, the cost parity year does not fully determine the adoption scenarios that will be modeled in the EFS and presented in future reports.

This report documents projected cost and performance assumptions for slow, moderate, and rapid technology advancement in electrification technologies across transportation and buildings sectors. The report also presents limited information available on electrotechnologies in the industrial sector. The report supports the Electrification Futures Study, which intends to explore aggressive yet plausible ranges of adoption of these technologies. Beyond supporting the EFS, the projections documented here represent expert evaluation of the results of a comprehensive literature search, and they provide data that may assist other electrification analysis and research.

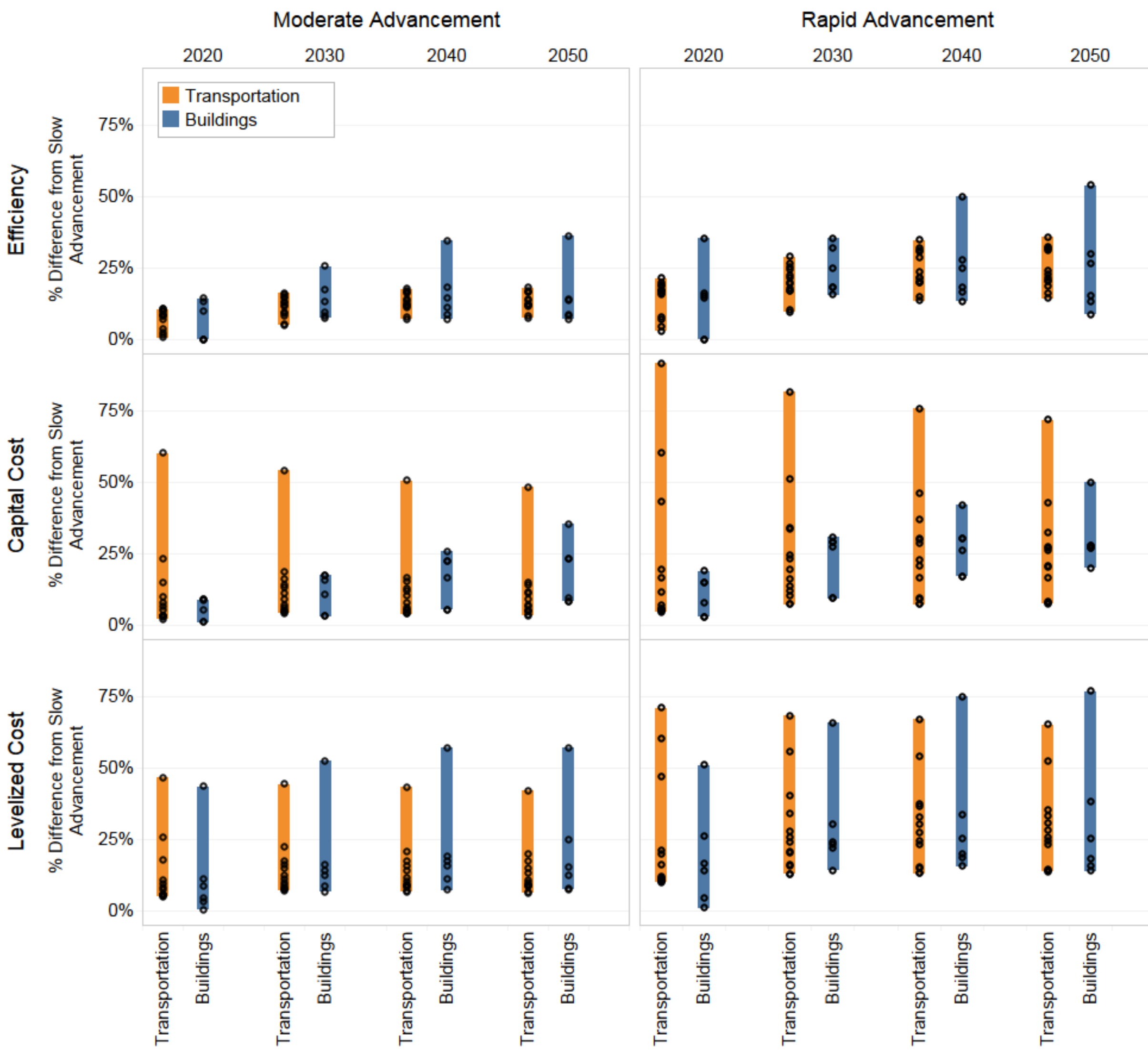

Figure 28. Percentage difference for each technology from Slow Advancement estimates versus Moderate and Rapid Advancement estimates, by sector.

Each colored bar represents the range of percentages by sector, and each black circle represents a specific technology. The percentage differences for each technology are listed in Appendix A.

Table 18. Summary of Sources and Methodologies

Technology	Metric	Primary Source Used for Projection		
		Slow Advancement	Moderate Advancement	Rapid Advancement
Transportation				
Light-Duty Vehicles	Capital Cost	Moawad et al. (2016) Low Cost case with updated battery costs from Curry (2017), DOE-VTO (Howell 2017; Islam et al. forthcoming)	Moawad et al. (2016) Medium Cost case with updated 2016 battery costs from Curry (2017)	Moawad et al. (2016) High Cost case with updated 2016 battery costs from Curry (2017)
	Fuel Economy	Moawad et al. (2016) Low Technology case	Moawad et al. (2016) Medium Technology case	Moawad et al. (2016) High Technology case
	Maintenance	Assumption, equivalent to ICEVs	Al-Alawi et al. (2016) and Mishra et al. (2013)	Assumption, 50% of ICEV for BEVs, and 75% of ICEVs for PHEVs
	Infrastructure	Melaina et al. (2016) high-cost values, DCFC costs from Francfort et al. (2017)	Melaina et al. (2016) moderate-cost values, DCDF costs from Francfort et al. (2017)	Melaina et al. (2016) low-cost values, DCFC costs from Francfort et al. (2017)
Medium-Duty Vehicles	Capital Cost	Calculated based on assumed battery range of 200 miles, and battery cost assumptions used for LDVs	Manufacturer specifications (BYD 2017), and battery cost assumptions used for LDVs	Calculated based on assumed battery range of 50 miles, and battery cost assumptions used for LDVs
	Fuel Economy	Assumed to reach 10% lower fuel economy than EIA (2017a) by 2050	EIA (2017a)	Assumed to reach 10% higher fuel economy than EIA (2017a) by 2050
	Maintenance	Assumption, equivalent to ICEVs	CARB	Assumption, 50% of ICEV
	Infrastructure	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power
Heavy-Duty Vehicles	Capital Cost	Manufacturer specifications (BYD 2017), and battery cost assumptions used for LDVs	Calculated based on assumed battery range of 200 miles, and battery cost assumptions used for LDVs	Calculated based on assumed battery range of 500 miles, and battery cost assumptions used for LDVs
	Fuel Economy	Assumed to reach 10% lower fuel economy than EIA (2017a) by 2050	EIA (2017a)	Assumed to reach 10% higher fuel economy than EIA (2017a) by 2050
	Maintenance	Assumption, equivalent to ICEVs	CARB (2017c)	Assumption, 50% of ICEV
	Infrastructure	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power
Buses	Capital Cost	Manufacturer specifications (Proterra 2017), and battery cost assumptions used for LDVs	Manufacturer specifications (Proterra 2017), and battery cost assumptions used for LDVs	Manufacturer specifications (Proterra 2017), and battery cost assumptions used for LDVs
	Fuel Economy	CARB (2017b) for current fuel economy, assumed to reach 10% lower incremental fuel economy improvements than HDVs in EIA (2017a) by 2050	CARB (2017b) for current fuel economy, assumed to same incremental improvements as HDV in EIA (2017a)	CARB (2017b) for current fuel economy, assumed to reach 10%higher incremental fuel economy improvements than HDVs in EIA (2017a) by 2050
	Maintenance	Assumption, equivalent to ICEVs	CARB (2017b)	Assumption, 50% of ICEV
	Infrastructure	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power	DCFC costs from Francfort et al. (2017), charger-to-vehicle ratio based on battery size and charger power

Technology	Metric	Primary Source Used for Projection		
		Slow Advancement	Moderate Advancement	Rapid Advancement
Buildings				
Residential Space Heating - Moderate/Warm Climates	Capital Cost	Reference price trend from Technical Support Document for standards (DOE 2016d)	High decreasing price trend from Technical Support Document for standards (DOE 2016d)	High range of target cost reduction from IEA (2011)
	Efficiency	Follows efficiency trajectory from NEMS/AEO2017 Reference case	2050 "typical" efficiency of adopted devices is equivalent to today's highest current efficiency. Current efficiency levels compiled from many sources (Baxter 2017a; Cadmus 2016; DOE 2014c; DOE 2016d; EIA 2017c, Lapsa and Khowailed 2014; Lapsa et al. 2017a; Navigant 2016; NEEP 2013; NEEP 2016; NEEP 2017b; Roberts et al. 2012).	Achieves maximum efficiency possible through vapor compression cycle - assumed to be 45% of Carnot Efficiency (DOE 2014b)
Residential Space Heating - Cold Climates	Capital Cost	Equivalent to moderate/warm climates	Equivalent to moderate/warm climates	Equivalent to moderate/warm climates
	Efficiency	Achieves DOE BTO target by 2050 (DOE 2014c)	Achieves DOE BTO target by 2040 (DOE 2014c) with moderate continued improvement thereafter	Achieves DOE BTO target by 2030 (DOE 2014c) with moderate continued improvement thereafter
Residential Water Heating	Capital Cost	Achieves DOE BTO target by 2050 (DOE 2014a)	Achieves DOE BTO target by 2030 (DOE 2014a)	Achieves DOE BTO target by 2020 (DOE 2014a)
	Efficiency	Achieves DOE BTO target by 2050 (DOE 2014a, Bouza 2016)	Achieves DOE BTO target by 2030 (DOE 2014a) with continued improvement to the IEA moderate target by 2050 (IEA 2011)	Achieves DOE BTO target by 2030 (DOE 2014a) with continued improvement to the IEA aggressive target by 2050 (IEA 2011)
Commercial Space Heating	Capital Cost	1/2 the rate of improvement from the reference price trend from the Technical Support Document for standards (DOE 2015a)	Reference price trend from the Technical Support Document for standards (DOE 2015a)	Achieves IEA (2011) aggressive target by 2050
	Efficiency	2050 typical efficiency equivalent to current highest efficiency systems (DOE 2015a, EIA 2017b, Navigant 2016)	Achieves IEA (2011) moderate target by 2050	Achieves IEA (2011) aggressive target by 2050
Commercial Space Heating - Cold Climates	Capital Cost	Equivalent to moderate/warm climates	Equivalent to moderate/warm climates	Equivalent to moderate/warm climates
	Efficiency	Achieves DOE target by 2040 (Bouza 2016)	Achieves DOE target by 2030 (Bouza 2016) and achieves residential ccASHP target by 2040 (DOE 2014c)	Achieves DOE target by 2020 (Bouza 2016) and achieves residential ccASHP target by 2030 (DOE 2014c)
DOE-VTO	Capital Cost	EnergyPATHWAYS; IEA technology roadmap - 1/2 the rate of improvement as achieved with the moderate target (IEA 2011)	EnergyPATHWAYS; IEA technology roadmap moderate target (IEA 2011)	EnergyPATHWAYS; IEA technology roadmap aggressive target (IEA 2011)
	Efficiency	Achieves mid- to high-range efficiency of currently available devices by 2020 and remains flat (EIA 2017b).	EnergyPATHWAYS; IEA technology roadmap moderate target (IEA 2011)	EnergyPATHWAYS; IEA technology roadmap aggressive target (IEA 2011)
Industry				
Not applicable				

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Appendix A

Transportation Infrastructure

For the analysis of cost sensitivities, infrastructure costs for the electrification of light-duty cars and trucks include the installation and capital cost of private and public electric vehicle supply equipment (EVSE). To conform to the EnergyPATHWAYS modeling framework, we allocate the infrastructure costs across vehicles to obtain a per-vehicle cost for model input. The NEVA study analyzes the projected units of each type of EVSE (Level 1, Level 2, DCFC) in various settings (e.g., home, workplace, and public settings) that would be built out to accommodate an aggressive adoption of PEVs (Melaina et al. 2016b). We use this allocation of EVSE units to PHEVs and BEVs to determine a per-vehicle cost. The costs used for the various Level 1 and Level 2 EVSE units were also taken from the NEVA study, which were based on DOE (2015c), National Research Council (2015), and CalETC (2014), and they included low and high cost sensitivities (based on a 10%–20% adjustment in cost). The DCFC costs were based on an analysis by the Idaho National Laboratory (Francfort et al. 2017), which evaluated DCFC station costs that can charge up to three vehicles simultaneously, with six 50-kW plugs.[76]

The per-vehicle cost for EVSE is calculated using the net present value of EVSE payments over the lifetime of the vehicle. The annual EVSE payments are calculated based on a 10-year lifetime (DOE 2015c); we assume a vehicle owner would pay for more than one EVSE if the vehicle lifetime exceeds 10 years. In the EFS accounting framework, each new sale of an electric vehicle that is replacing a conventional vehicle will incur the capital cost and installation cost for new EVSE. For every replacement sale (e.g., replacement of an electric vehicle with another electric vehicle), we assume only the capital cost and 30% of the installation cost will be incurred. The remaining 70% of installation costs is assumed to be wiring and electrical upgrades that have long lifetimes (DOE 2015c) and would not be replaced during the timeframe of EFS projections.

For medium- and heavy-duty trucks and electric buses, we assume DCFC is required to support the duty cycles of this subsector. As with LDVs, DCFC costs are based on the Idaho National Laboratory analysis (Francfort et al. 2017). For heavy-duty trucks and buses, we assume a 350-kW charger is used,[77] because of the larger battery sizes of those vehicles. For medium-duty trucks, we assume the 50-kW charger is used. We assume the charger is operated for 10 hours a day, and the costs are allocated across the number of vehicles that can be charged in that time frame, based on based battery size. The 350-kW and 50-kW charging stations in Francfort et al. (2017) have peak power outputs of 1,050 kW and 150 kW respectively. We divide the peak power output over an assumed 10 hour shift by the vehicle battery size, assuming an 80% depth of discharge to calculate the number of vehicles per DCFC.[78]

Catenary Infrastructure

This analysis considers only DCFC infrastructure for heavy-duty applications, but alternative potential charging infrastructure technologies exist, or are being considered, including overhead

[76] The station costs were divided by three to calculate a per-vehicle DCFC cost.
[77] There are examples of values as high as 400-500 kW proposed in the literature (Eudy et al. 2016; ChargePoint 2017).
[78] The calculation assumptions are based on a similar analysis from CALSTART (2013)

catenary charging, in-road inductive charging, and battery swapping. For comparison to our assumptions of DCFC costs, we estimate the costs of catenary charging infrastructure, which is most likely to be implemented for heavily-used HDV corridors, possibly with a dedicated HDV fleet, as might occur in some drayage applications. Catenary charging for HDVs is already being demonstrated in small-scale applications such as the Siemens eHighway projects in California (Riddett 2015) and Germany (Williams 2017). We use simplified assumptions about technology and maintenance costs, as well as an assumed level of buildout to support the HDV electrification. We use a per-mile overhead catenary infrastructure cost from den Boer et al. (2013) and note a gap in additional literature sources with projected technology costs.[79] den Boer et al. (2013) also provide a per-mile cost estimate for inductive charging infrastructure, which is the same as the catenary estimate; the maintenance cost for inductive charging is estimated to be 1% of the initial investment cost per year. Table A-1 shows the per-vehicle infrastructure cost that represents catenary charging and the primary calculation assumptions. Our review of the literature indicates that future infrastructure equipment costs, particularly for novel applications such as long-distance catenary or inductive equipment, are highly speculative and greater research is needed to estimate future technology possibilities and costs.

Table A-1. Per Vehicle Catenary Charging Infrastructure Costs and Assumptions

Data Element	Value	Notes
Catenary charging infrastructure cost per mile (2016$)	5 million	Based on den Boer et al. (2013)
Annual maintenance cost (2016$)	125,000	Based on 2.5% of initial investment cost per year (den Boer et al. 2013)
Miles to electrify	24,000	Assumed to be half of the U.S. interstate system[a]
Infrastructure lifetime (years)	20	Based on den Boer et al. (2013)
Per electric HDV cost (2016$)	**$34,653**	Net present value over vehicle lifetime

[a] We assume half of the interstate system to reflect the assumption planned for use in the EFS adoption scenario for high electrification, which is that half of HDV sales will be BEVs in 2050.

[79] We expect cost estimates to become available with the progression of current demonstration projects.

Transportation Levelized Cost of Driving

The levelized cost of driving represents the cost per mile over the lifetime of the vehicle. For the cost parity analysis in Section 2.2, the LCOD was calculated using the following equation:

$$LCOD = \frac{CRF * (CC + I) + M}{VMT} + \frac{GP\ * \%G}{MPG_G} + \frac{DP\ * \%D}{MPG_D} + \frac{EP * \%E}{MPG_{Elec}}$$

CRF	capital recover factor, equal to $\frac{D(1+D)^N}{(1+D)^N-1}$, where D is the discount rate, and N is vehicle lifetime in years
CC	capital cost of the vehicle, not including infrastructure costs
I	net present value of infrastructure costs over lifetime of the vehicle
M	annual vehicle maintenance costs
VMT	annual vehicle miles traveled
GP	gasoline price in dollars per gallon
DP	diesel price in dollars per gallon gasoline equivalent (gge)
EP	electricity price in dollars per gge
%G	percent of miles driven on gasoline (this equals 1 for conventional gasoline vehicles and 1-utility factor for PHEVs)
%D	percent of miles driven on diesel (this equals 1 for conventional diesel vehicles and 0 for all others)
%E	percent of miles driven on electricity (this equals 0 for conventional vehicles and 1 for BEVs, and it is equal to the utility factor for PHEVs)
MPG_G	fuel economy on gasoline in MPGe
MPG_D	fuel economy on diesel in MPGe
MPG_{Elec}	fuel economy on electricity in MPGe

The cost and performance projections presented in Section 2.1 are used for the vehicle costs. The fuel prices are based on AEO trajectories, which were used to calculate the discount weighted fuel price over the life time of the vehicle for the respective year. Table A-2 shows the calculated discount rate-weighted fuel prices, based on the assumed vehicle lifetime. We assume the 2050 AEO fuel price stays constant in all future years.

Table A-2. Discount Rate Weighted Fuel Price Calculations, with a 10% Discount Rate

Vehicle Lifetime (Years)	Fuel Type	Units	Discount Rate Weighed Fuel Price			
			2020	2030	2040	2050
10	Diesel	$/gal	3.43	3.89	4.10	4.23
		$/gge	3.88	4.39	4.63	4.78
	Electricity	$/kWh	0.13	0.14	0.13	0.13
		$/gge	4.36	4.59	4.48	4.47
	Gasoline	$/gal	2.84	3.13	3.34	3.42
		$/gge	2.84	3.13	3.34	3.42
15	Diesel	$/gal	3.51	3.92	4.12	4.23
		$/gge	3.97	4.43	4.66	4.78
	Electricity	$/kWh	0.13	0.14	0.13	0.13
		$/gge	4.41	4.57	4.48	4.47
	Gasoline	$/gal	2.88	3.17	3.35	3.42
		$/gge	2.88	3.17	3.35	3.42

Levelized Cost of Driving Sensitivity

The LCOD results presented in Section 2.2 are dependent on the cost and performance projections in Section 2.1 and the input assumptions described above. Vehicle purchase price is a major driver in the LCOD for LDVs, as shown in Figure 13. As noted in Section 2.2, cost can vary within each powertrain, depending on vehicle make and model, which means there is also a range of LCODs for each powertrain; Figure A-1 shows the range of MSRP and fuel economy for model-year 2015 vehicles.

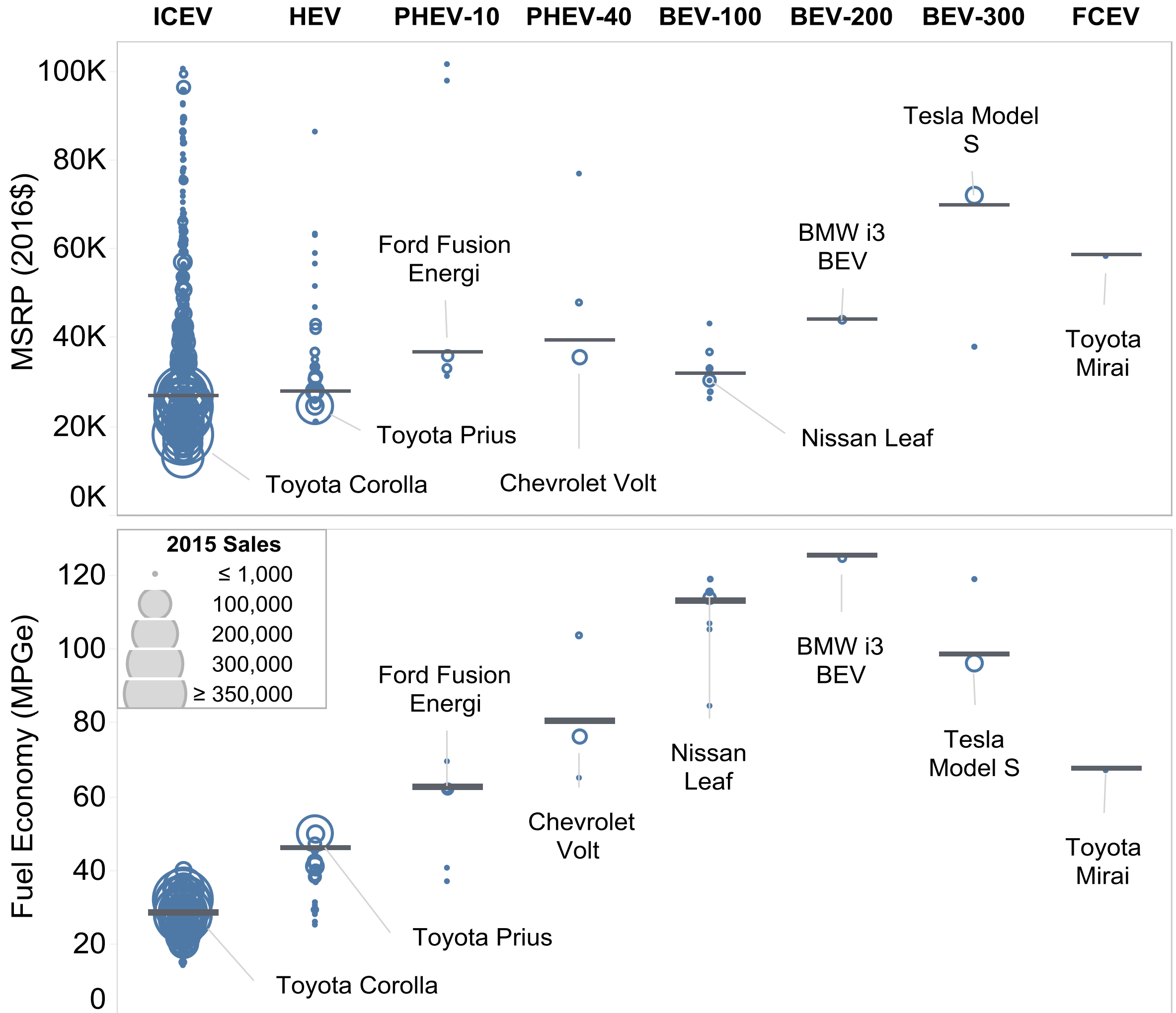

Figure A-1. MSRP and fuel economy of model-year 2015 light-duty cars, with sales-weighted average (grey line)

Sources: Wards Automotive (MSRP) and IHS Automotive (sales)

Data were compiled for the NREL Automotive Deployment Options Projection Tool (ADOPT) vehicle choice model (Brooker et al. 2015) by Russ Campbell, CSRA Inc.

Vehicle models with an MSRP exceeding $100,000 are not shown.

Highest selling model within each powertrain is noted.

The input assumptions in the LCOD calculation also affect the relative LCOD between vehicle technologies in each subsector. To assess the relative impact of discount rate, vehicle miles traveled, and vehicle lifetime on the calculated LCOD, we perform a simple sensitivity analysis of these factors. Figures A-2, A-3, and A-4Figure show the absolute LCOD and the LCOD proportion by cost component for varying discount rates, vehicle miles traveled, and vehicle lifetime. The gap between the LCOD of conventional and electric vehicle technologies increases with discount rate, shown in Figure A-2Figure, due to the higher capital costs of electric vehicles. The capital cost component of the LCOD also increases with discount rate. Conversely, FigureFigures A-3 and A-4 show that as vehicle miles traveled and vehicle lifetime increase respectively, the capital cost component of the LCOD decreases, and fuel cost becomes a greater factor.

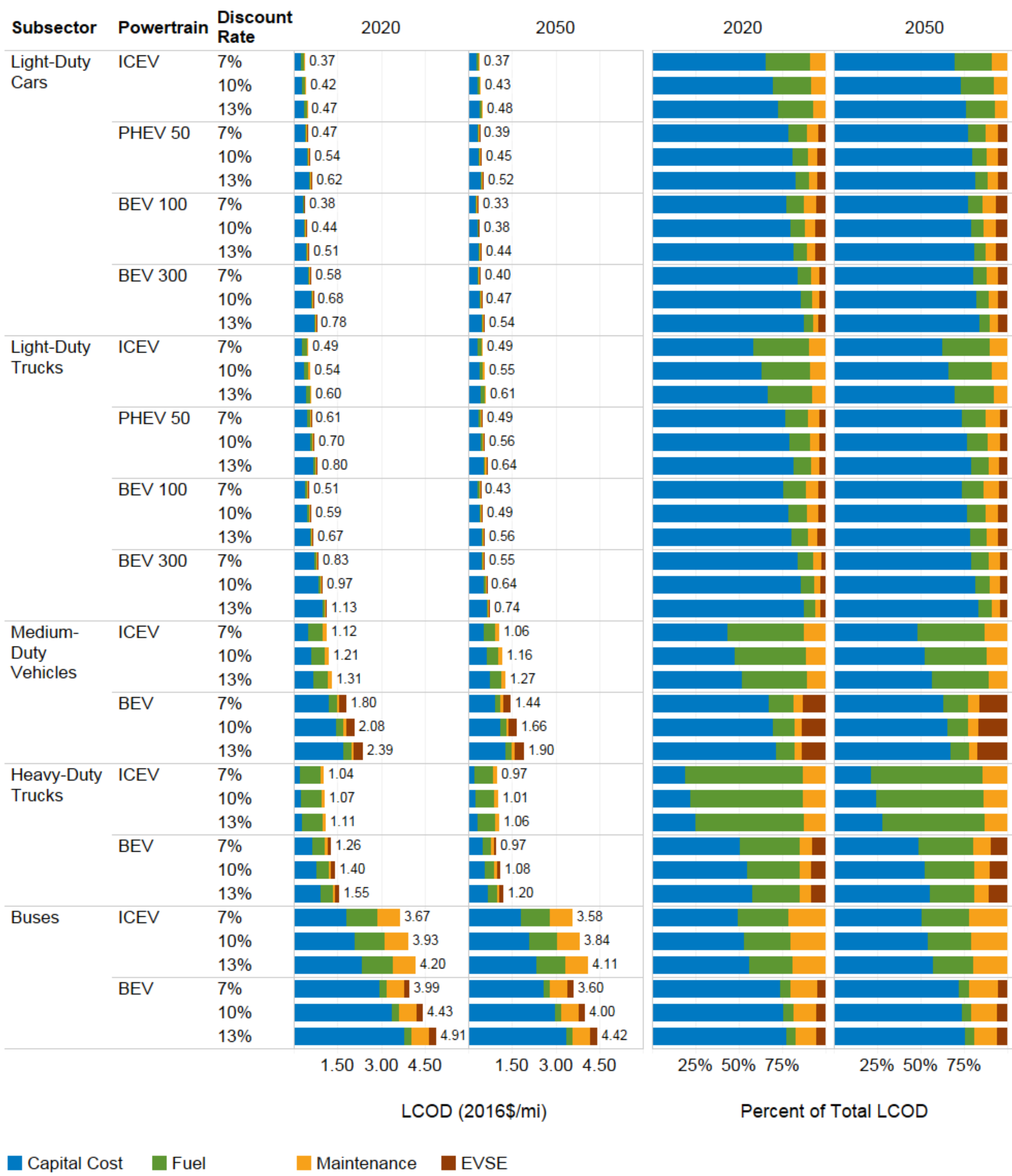

Figure A-2. LCOD sensitivity for discount rate in 2020 and 2050 for the Moderate Advancement projection

All powertrains within each vehicle class are assumed to be driven the same number of miles.

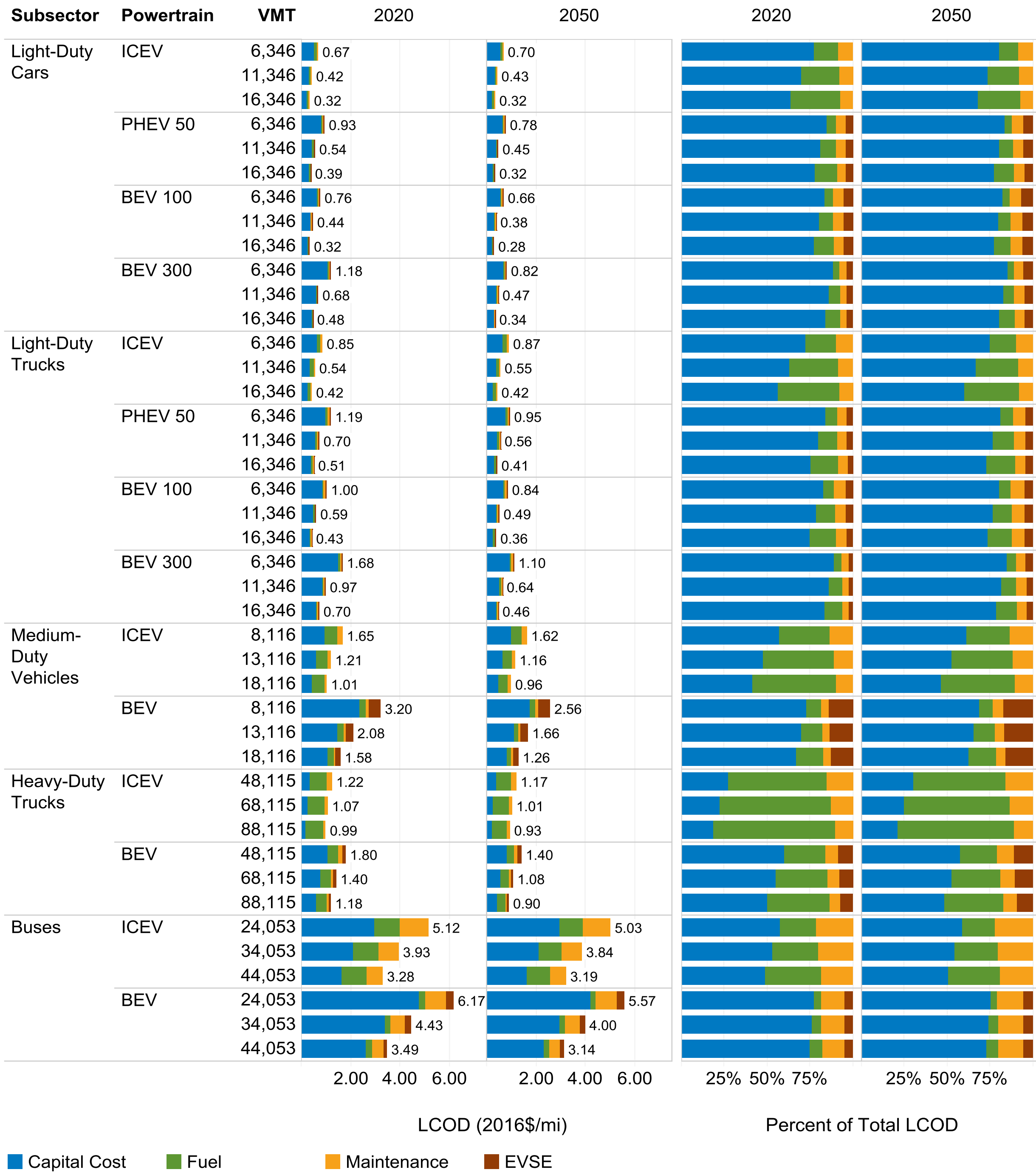

Figure A-3. LCOD sensitivity for annual vehicle miles traveled in 2020 and 2050 for the Moderate Advancement projection

All powertrains within each vehicle class are assumed to be driven the same number of miles.

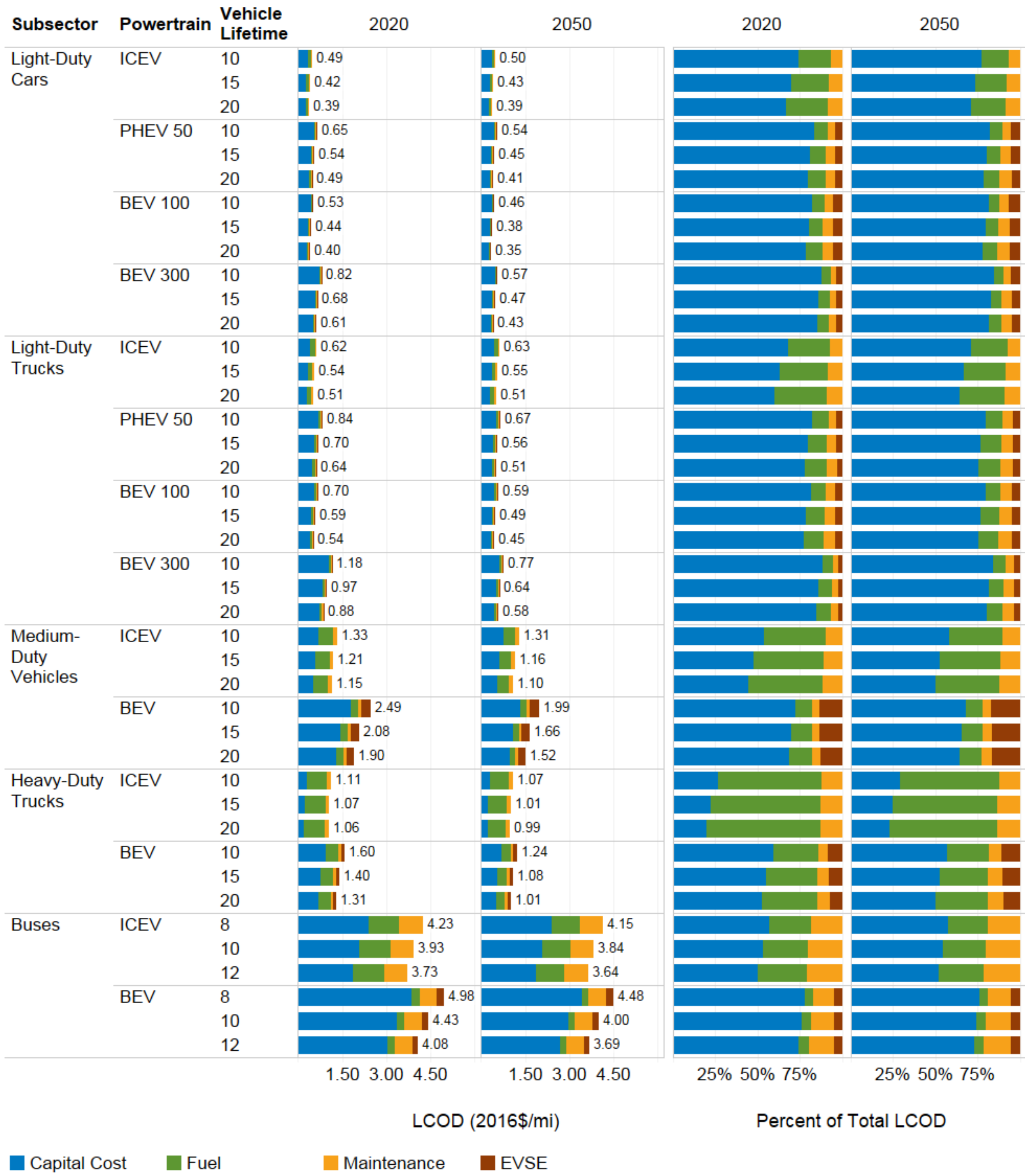

Figure A-4. LCOD sensitivity for vehicle lifetime (years) in 2020 and 2050 for the Moderate Advancement projection

All powertrains within each vehicle class are assumed to be driven the same number of miles.

Buildings Levelized Cost of Services

The levelized cost of services (LCOS) represents the cost per unit of service delivered from a specific technology levelized across the lifetime of the technology. For each technology and associated end-use service, LCOS calculation can differ slightly but can be generalized according to the following equation:

$$LCOS = \frac{CRF * CapCost}{Service} + \frac{CRF * NPVFuel_{y \ldots y+l}}{EE_y} + AnnMaint$$

AnnMaint	annual maintenance cost over the lifetime of the technology
CapCost	capital cost of the technology including installation costs
CRF	capital recovery factor equal to $\frac{D(1+D)^l}{(1+D)^l - 1}$, where D is the discount rate
EE_y	energy efficiency of the technology in the adoption year, y
$NPVFuel_{y \ldots y+l}$	net present value of fuel prices over the lifetime of the technology (from the adoption year, y, to the end of its lifetime in year $y + l$, where l, is the lifetime)
Service	annual service consumption

LCOS calculations assume a discount rate of 10% for residential technologies and 7% for commercial technologies. Impacts of varying the discount rate are shown in the next section. Lifetimes and maintenance costs assumptions are detailed in Table A-3. For residential space heating, we assume delivered service (heating) of 50 MMBtu per year. For water heating, we assume delivered service (heating) of 15 MMBtu per year. To calculate service values for commercial end uses, we assume annual capacity factors of 8% for space heating and 25% for water heating.

Table A-3. Input Assumptions for the LCOS Calculations

Sector	Subsector	Technology	Lifetime (years)	Maintenance Cost
Residential	Space heating	ASHP	16	$76/yr
		NG furnace	16	$45/yr
		Elec. resistance	25	$40/yr
	Water heating	HPWH	13	$16/yr
		NG storage water heater	13	$14/yr
		Elec. resistance storage water heater	13	$6/yr
Commercial	Space heating	ASHP	15	$1.47/kBtu/hr/yr
		NG furnace	15	$1.03/kBtu/hr/yr
		Elec. resistance	18	$0.01/yr
	Water heating	HPWH	13	$2.29/kBtu/hr/yr
		NG storage water heater	13	$0.55/kBtu/hr/yr
		Elec. resistance storage water heater	13	$0.88/kBtu/hr/yr

Buildings Levelized Cost of Service Sensitivity

Section 3.2 presents the levelized cost of service metrics for the Slow, Moderate, and Rapid Advancement projections calculated using our reference assumptions. As shown above, fuel costs and associated future fuel expenditures are a key driver of the LCOS and the cost parity between technologies. The impact of future fuel prices on the LCOS is determined by the discount rate. Figure A-5 and Figure A-6 show how the LCOSs change with alternative assumed discount rates.

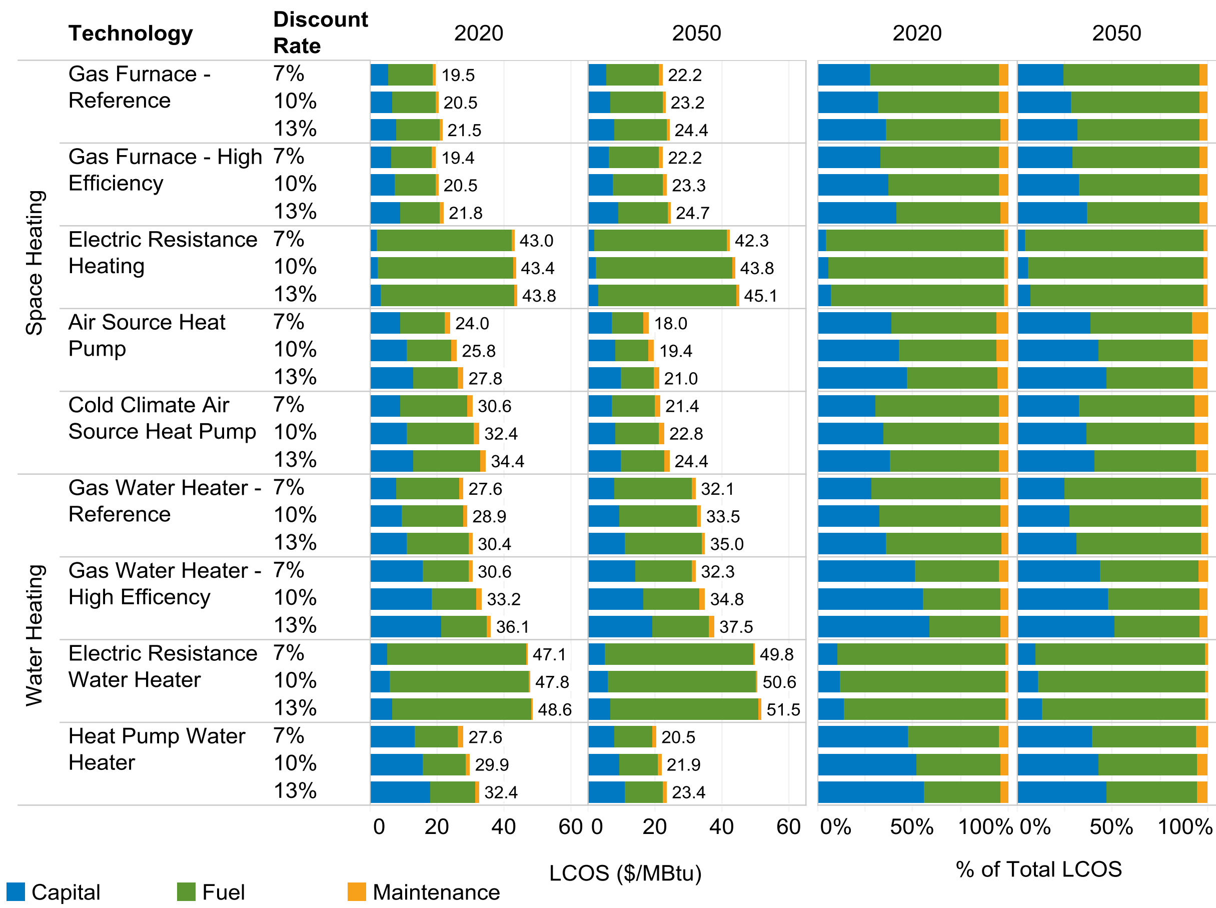

Figure A-5. Sensitivity of residential sector LCOSs to discount rate chosen

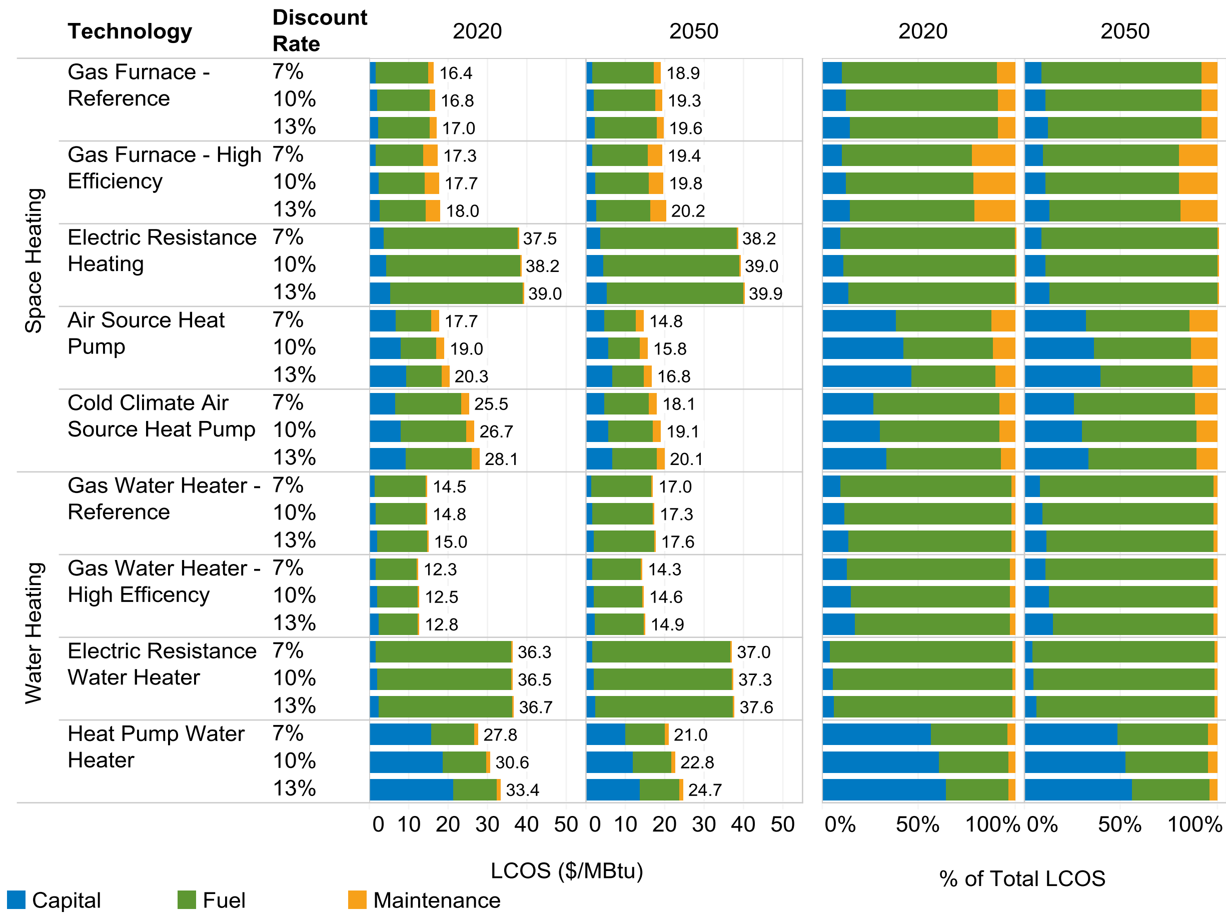

Figure A-6. Sensitivity of commercial sector LCOSs to discount rate chosen

Summary Data

Tables A-4 and A-5 list the percentage difference between the estimates for the Slow Advancement case and Moderate and Rapid Advancement cases, for transportation and buildings technologies. These data are also represented in Figure 28 in Section 5.

Table A-4. Summary of the Percentage Differences between the Slow Advancement and the Moderate and Rapid Advancement Estimates for Transportation Technologies

			% Difference of Moderate Advancement Estimate vs. Slow Advancement				% Difference of Rapid Advancement Estimate vs. Slow Advancement			
Metric	**Subsector**	**Technology**	2020	2030	2040	2050	2020	2030	2040	2050
Efficiency	Light-Duty Cars	BEV 100	8%	14%	16%	16%	16%	24%	30%	32%
		BEV 200	9%	15%	16%	17%	17%	25%	31%	32%
		BEV 300	10%	16%	17%	17%	19%	27%	32%	32%
		PHEV 25	1%	8%	14%	14%	8%	18%	29%	31%
		PHEV 50	11%	16%	18%	18%	21%	29%	35%	36%
	Light-Duty Trucks	BEV 100	8%	12%	12%	12%	16%	19%	20%	20%
		BEV 200	9%	12%	12%	12%	17%	20%	20%	21%
		BEV 300	10%	13%	13%	12%	19%	22%	22%	21%
		PHEV 25	7%	9%	11%	11%	17%	17%	20%	18%
		PHEV 50	10%	13%	13%	13%	20%	22%	24%	24%
	Medium-Duty Trucks	BEV	1%	5%	8%	8%	3%	10%	15%	16%
	Heavy-Duty Trucks	BEV	4%	9%	11%	12%	7%	17%	22%	23%
	Buses	BEV	2%	5%	7%	7%	4%	10%	13%	14%
Capital Cost	Light-Duty Cars	BEV 100	2%	4%	5%	5%	4%	13%	17%	16%
		BEV 200	5%	9%	8%	7%	11%	19%	23%	20%
		BEV 300	8%	14%	13%	12%	16%	25%	30%	27%
		PHEV 25	3%	4%	4%	3%	5%	7%	7%	7%
		PHEV 50	3%	6%	5%	5%	6%	10%	9%	8%
	Light-Duty Trucks	BEV 100	3%	5%	6%	7%	5%	16%	21%	20%
		BEV 200	7%	11%	10%	9%	7%	23%	29%	26%
		BEV 300	10%	16%	15%	14%	19%	34%	37%	32%
		PHEV 25	3%	5%	4%	3%	5%	7%	7%	8%
		PHEV 50	3%	7%	5%	5%	6%	12%	9%	8%
	Medium-Duty Trucks	BEV	15%	13%	12%	11%	60%	51%	46%	43%
	Heavy-Duty Trucks	BEV	60%	54%	51%	48%	92%	81%	76%	72%
	Buses	BEV	23%	19%	16%	15%	43%	34%	30%	27%
Levelized Cost	Light-Duty Cars	BEV 100	5%	8%	8%	9%	12%	20%	23%	23%
		BEV 200	7%	11%	10%	10%	16%	24%	27%	26%
		BEV 300	9%	15%	14%	13%	20%	28%	33%	31%
		PHEV 25	5%	7%	7%	6%	10%	13%	13%	14%
		PHEV 50	6%	9%	9%	9%	11%	16%	15%	14%
	Light-Duty Trucks	BEV 100	6%	8%	9%	9%	11%	21%	25%	24%
		BEV 200	8%	12%	11%	11%	11%	26%	30%	28%
		BEV 300	11%	16%	16%	15%	21%	34%	37%	33%
		PHEV 25	5%	7%	7%	6%	10%	13%	13%	14%
		PHEV 50	6%	10%	9%	9%	10%	16%	15%	14%
	Medium-Duty Trucks	BEV	18%	17%	17%	17%	60%	56%	54%	52%
	Heavy-Duty Trucks	BEV	47%	44%	43%	42%	71%	68%	67%	65%
	Buses	BEV	25%	22%	21%	20%	47%	40%	37%	35%

1% [color scale] 92%

Table A-5. Summary of the Percentage Differences between the Slow Advancement and the Moderate and Rapid Advancement Estimates for Buildings Technologies

Metric	Subsector	Technology	% Difference of Moderate Advancement Estimate vs. Slow Advancement				% Difference of Rapid Advancement Estimate vs. Slow Advancement			
			2020	2030	2040	2050	2020	2030	2040	2050
Efficiency	Residential Space Heating	ASHP	14%	26%	34%	36%	14%	32%	50%	54%
		ccASHP	0%	10%	9%	8%	0%	18%	17%	15%
	Residential Water Heating	HPWH	0%	7%	7%	7%	15%	16%	13%	13%
	Commercial Space Heating	ASHP	10%	13%	14%	14%	16%	25%	28%	30%
		ccASHP	13%	17%	18%	9%	35%	35%	18%	9%
	Commercial Water Heating	HPWH	0%	8%	11%	13%	0%	18%	25%	27%
Capital Cost	Residential Space Heating	ASHP	1%	3%	5%	8%	3%	9%	17%	27%
		ccASHP	1%	3%	5%	8%	3%	9%	17%	27%
	Residential Water Heating	HPWH	9%	11%	17%	10%	19%	31%	26%	20%
	Commercial Space Heating	ASHP	9%	17%	22%	23%	15%	29%	30%	28%
		ccASHP	9%	17%	22%	23%	15%	29%	30%	28%
	Commercial Water Heating	HPWH	5%	16%	26%	35%	8%	27%	42%	50%
Levelized Cost	Residential Space Heating	ASHP	43%	52%	57%	57%	51%	66%	75%	77%
		ccASHP	0%	7%	7%	8%	1%	14%	16%	18%
	Residential Water Heating	HPWH	5%	9%	11%	7%	17%	22%	19%	16%
	Commercial Space Heating	ASHP	9%	14%	16%	15%	14%	24%	25%	25%
		ccASHP	11%	16%	17%	12%	26%	30%	20%	14%
	Commercial Water Heating	HPWH	3%	12%	19%	25%	5%	23%	33%	38%

0% [color scale] 77%

Appendix B

Climate Zone Map

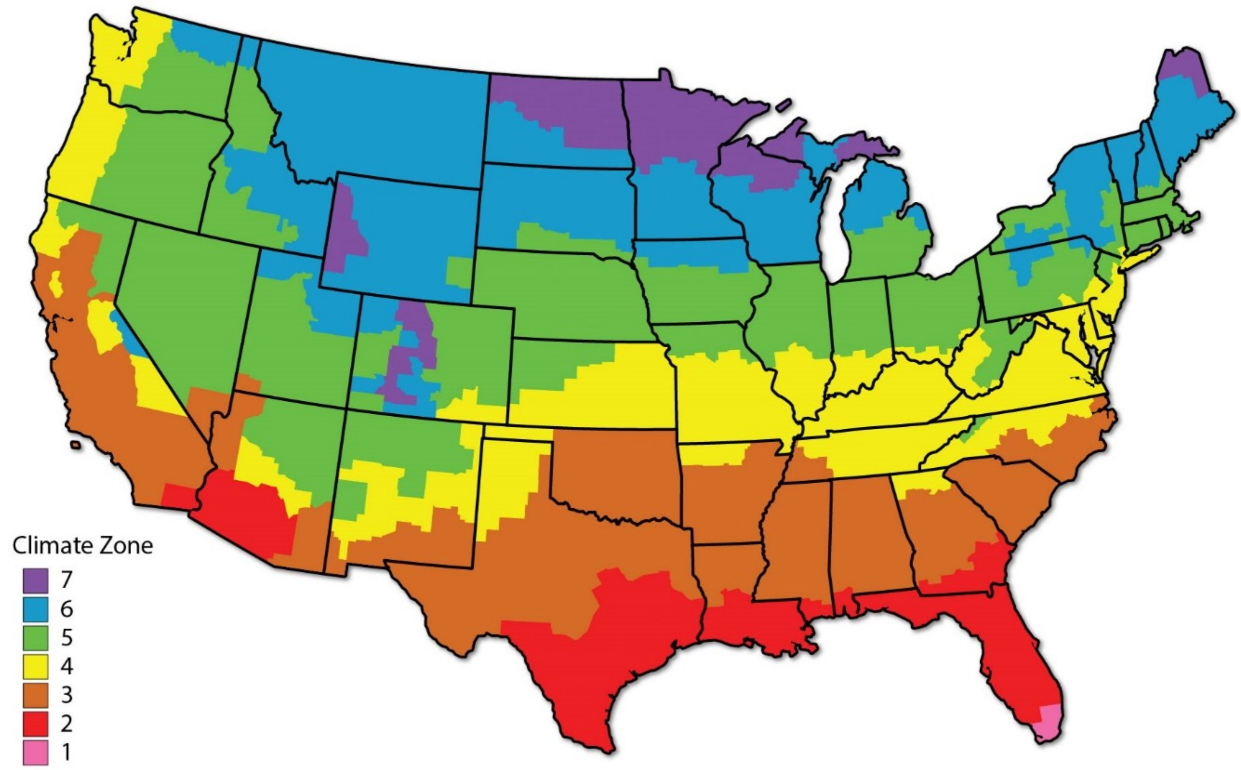

Figure B-1. Climate zone map

Based on the International Energy Conservation Code climate zone map

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