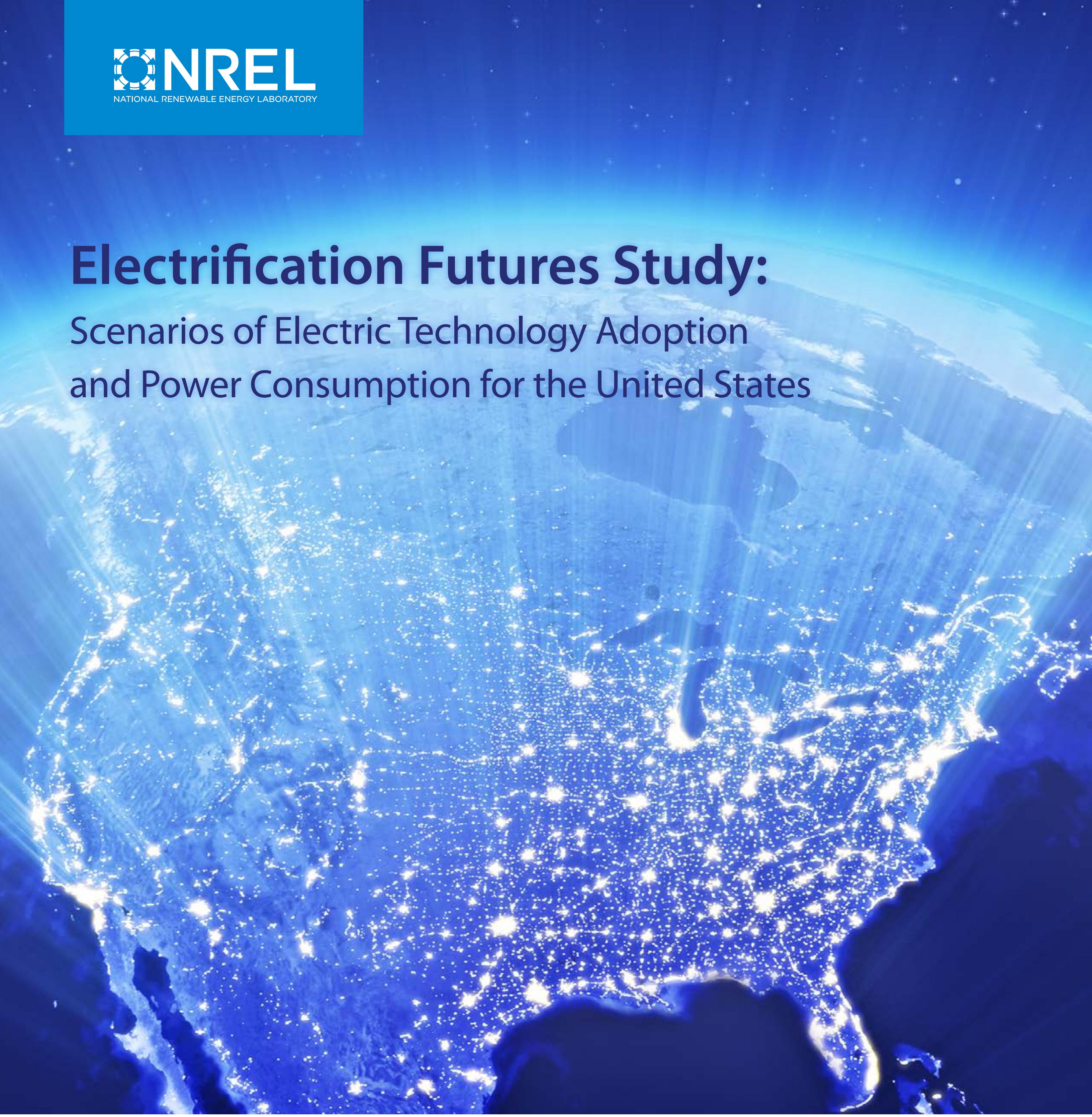

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Electrification Futures Study:

Scenarios of Electric Technology Adoption and Power Consumption for the United States

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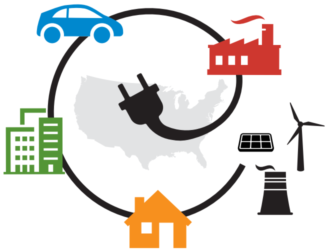

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NOTICE

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Preface

This report is one in a series of Electrification Futures Study (EFS) publications. The EFS is a multi-year research project to explore potential widespread electrification in the future energy system of the United States. Electrification is defined as the substitution of electricity for direct combustion of non-electricity-based fuels (e.g., gasoline and natural gas) used to provide similar services.

The EFS is specifically 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 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	Provides technology data used in this report (Jadun et al. 2017)
Electrification demand-side adoption scenarios	*This report*
Electric system supply-side scenarios	Relies on electricity consumption reported in this report
Electricity consumption patterns	Relies on technology adoption projections reported in this report
Electric system operations	Relies on the consumption patterns and supply-side scenarios from other reports, which rely on data from this report
Impacts assessment	Relies on the technology adoption projections in this report along with data from other reports

This report is the second publication in this series and presents scenarios of electric end-use technology adoption and resulting electricity consumption in the United States. The scenarios reflect a wide range of electricity demand growth through 2050 that result from various electric technology adoption and efficiency projections in the transportation, residential and commercial buildings, and industrial sectors. The report describes the methodology, assumptions, and limitations of the analysis. The demand scenarios provided in this report will be used to inform the supply scenarios and impacts to be presented in future reports under the EFS project. Results from the current demand-side scenarios can also be used by other researchers who wish to explore implications of electrification and demand growth in the U.S. economy.

More information, the supporting data associated with this report, links to other reports in the EFS study, 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 on the following page. 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)
National Renewable Energy Laboratory

Sam Baldwin
U.S. Department of Energy

Steve Brick
Clean Air Task Force

Steve Clemmer
Union of Concerned Scientists

Laura Cozzi
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Francisco de la Chesnaye
Electric Power Research Institute

Keith Dennis
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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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Primary funding support for the EFS is provided by the DOE Office of Energy Efficiency and Renewable Energy Office of Strategic Programs. We especially thank Steve Capanna and Paul Donohoo-Vallett of DOE for their support and leadership throughout the EFS and for this report.

List of Acronyms and Abbreviations

ADOPT	Automotive Deployment Options Projection Tool
AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
ASHP	air source heat pump
BEV	battery electric vehicle
CAGR	compound annual growth rate
CBECS	Commercial Buildings Energy Consumption Survey
CDD	cooling degree day
DCFC	direct current fast charger
DOE	U.S. Department of Energy
EFS	Electrification Futures Study
EIA	U.S. Energy Information Administration
FERC	Federal Energy Regulatory Commission
GDP	gross domestic product
HDD	heating degree day
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle
HVAC	heating, ventilation, and air conditioning
IEA	International Energy Agency
LDV	light-duty vehicle
LED	light-emitting diode
MDV	medium-duty vehicle
MECS	Manufacturing Energy Consumption Survey
NAICS	North American Industry Classification System
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicles
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RECS	Residential Energy Consumption Survey
USD	U.S. dollars
VMT	vehicle miles traveled

Executive Summary

Motivation

Electrification—the shift from any non-electric source of energy to electricity at the point of final consumption—is a major emerging trend in energy markets around the world. Driving this trend is a collection of newly-improved electric end-use technologies, engaged consumers and manufacturers, and a variety of policy objectives in different jurisdictions. As energy and electricity impact every other sector of the economy, electrification has the potential to significantly affect actors across the entire landscape. Many electric utilities are carefully watching the trend toward electrification, as it has the potential to increase sales and revenues that have stagnated or fallen over the past decade. Beyond power system planning, other motivations to study electrification include its potential to impact energy security, emissions, and innovation in electrical end-use technologies and overall efficient system integration. The impacts of electrification could be far-reaching and have benefits and costs to various stakeholders.

This report—the second in the multi-year and multi-stakeholder Electrification Futures Study (EFS)—aims to build an integrated understanding of how the potential for electrification might impact the demand side in all major sectors of the U.S. energy system: transportation, residential and commercial buildings, and industry. The demand-side analysis presented in this report is not intended to be predictive but is instead designed to provide foundational data to enable a thorough assessment of the isolated impacts of electrification.

Individually, each sector would be impacted by increased electrification, and in aggregate, they could have notable effects on the future power system. Continued acceleration of electric vehicle adoption in the transportation sector could dramatically increase total electricity demand, with concurrent impacts on petroleum trade and tailpipe emissions. Impacts in this sector could be especially magnified because transportation currently accounts for less than 1% of U.S. electricity demand but accounts for nearly 30% of primary energy consumption. While energy consumption in buildings is already highly electrified, adoption of increasingly competitive commercial and residential high-efficiency electric heat pumps could significantly alter the shape and timing of peak electricity demand. Even though the broad heterogeneity of industrial uses limits generalizations, productivity and economic benefits of electrotechnologies for certain low-temperature energy needs, such as curing and drying, could lead to increased electrification in the sector.

Electricity provided about 19% of final U.S. energy consumption in 2016, but with a wide range across sectors: from about 0.1% in transportation to 53% in commercial buildings. The degree by which electrification might expand beyond this level could have significant implications for the U.S. and global economies, geopolitics, businesses, population, and the environment. The EFS is designed to evaluate some of these impacts while this report aims to accomplish two objectives:

1. Characterize changes to end-use sectors under futures with increasing levels of electrification
2. Quantify how electrification impacts total electricity demand and consumption profiles.

By exploring the impact of electrification on how much, when and where electricity is used, the demand-side scenarios presented here lay the foundation for future EFS reports on the electricity system's supply-side evolution and operations, as well as other impacts of electrification.

Scenario and Methods

This analysis presents plausible electrification scenarios encompassing end-use technology adoption across all sectors in the contiguous U.S. energy system through 2050. The end uses considered for electrification include all on-road transport, most of the buildings sector, and parts of the industrial sector, which together currently consume three-quarters of total U.S. primary energy and have market-ready or near market-ready electric technologies available.[1] For the analysis, we developed three main scenarios that explore the *speed and extent of consumer adoption* of end-use electric technologies from today through to 2050:

- **Reference scenario:** the least incremental change in electrification through 2050, which serves as a baseline of comparison to the other scenarios.[2]
- **Medium scenario:** a future with widespread electrification among the "low-hanging fruit" opportunities in electric vehicles, heat pumps and select industrial applications, but one that does not result in transformational change.
- **High scenario:** a combination of technology advancements, policy support and consumer enthusiasm that enables transformational change in electrification.

For each adoption scenario noted above, three scenarios explore the *rate of improvement* of key electric technologies from a cost and performance perspective, based on our best current understanding of how these traits will evolve over time and which a previous report in this series[3] explored. These nine scenarios capture a broad uncertainty range and together, span a considerable range of electrification futures. The scenarios are designed to assess impacts of potential widespread electrification and should not be interpreted as forecasts or predictions.

The scenarios were developed through use of an updated version of EnergyPATHWAYS (EP), a bottom-up stock-taking tool of all infrastructure that consumes, produces, delivers or converts energy. Annual sales shares in each scenario were developed through expert judgment from the authors based on analysis of current trends and insights from other studies as well as from consumer choice models. These sales shares are input to the tool, which tracks service demand changes, equipment stock turnover to meet those changes and consequential final energy and electricity use of: vehicle fleets; appliances; heating, ventilation, and air conditioning systems; industrial machinery; and other types of energy-consuming equipment over time. For this analysis, we focus only on direct electric technologies and isolate the impacts of electrification; we make no attempt to compare a broader suite of technology or fuel (e.g., hydrogen- or biomass-based) options, nor do we model macroeconomic or behavioral changes caused by new technology adoption.

In short, while the bottom-up accounting structure of EP has limitations, it does enable EP to comprehensively characterize long-term changes in the end-use ecosystem of technologies across sectors in future scenarios.

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[1] The one-quarter of total U.S. primary energy demand *not* considered for electrification in the analysis includes air, marine, rail and off-road transport; several "other" categories of building energy demand; and select industrial processes such as blast furnace steelmaking and petroleum refining.

[2] The Reference scenario is largely consistent with the U.S. Energy Information Administration's AEO2017 Reference scenario, which reflects laws, policies, and regulations as of 2017.

[3] The first report in the EFS series, *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050* (Jadun et al. 2017), provides data projections for multiple electric vehicle and heat pump technologies. It also summarizes the literature for industrial electrotechnologies.

Key Findings

The scale of electrification can be informed by the context of historical energy transformations. Rapid adoption of refrigerators, air conditioning, and home electronics, for example—coupled with population and economic growth—led to strong growth in commercial and residential electrification over the past several decades. In recent years, this overall growth in electricity share has leveled off but with the potential for future growth driven by technology adoption. Technology and energy transitions are often represented by S-shaped curves (Figure ES-1) that show slow initial growth, followed by rapid market uptake and then gradual leveling off as markets mature and saturate. Historical experiences suggest that technology diffusion, while notoriously difficult to predict, can occur rapidly and with an extensive reach. For this report, we use the S-curve behavior to inform the adoption of end-use electric technologies in the report's future scenarios. Our findings demonstrate a wide range of potential electrification levels, with associated impacts, depending on how technology, consumer choice and policy interventions evolve.

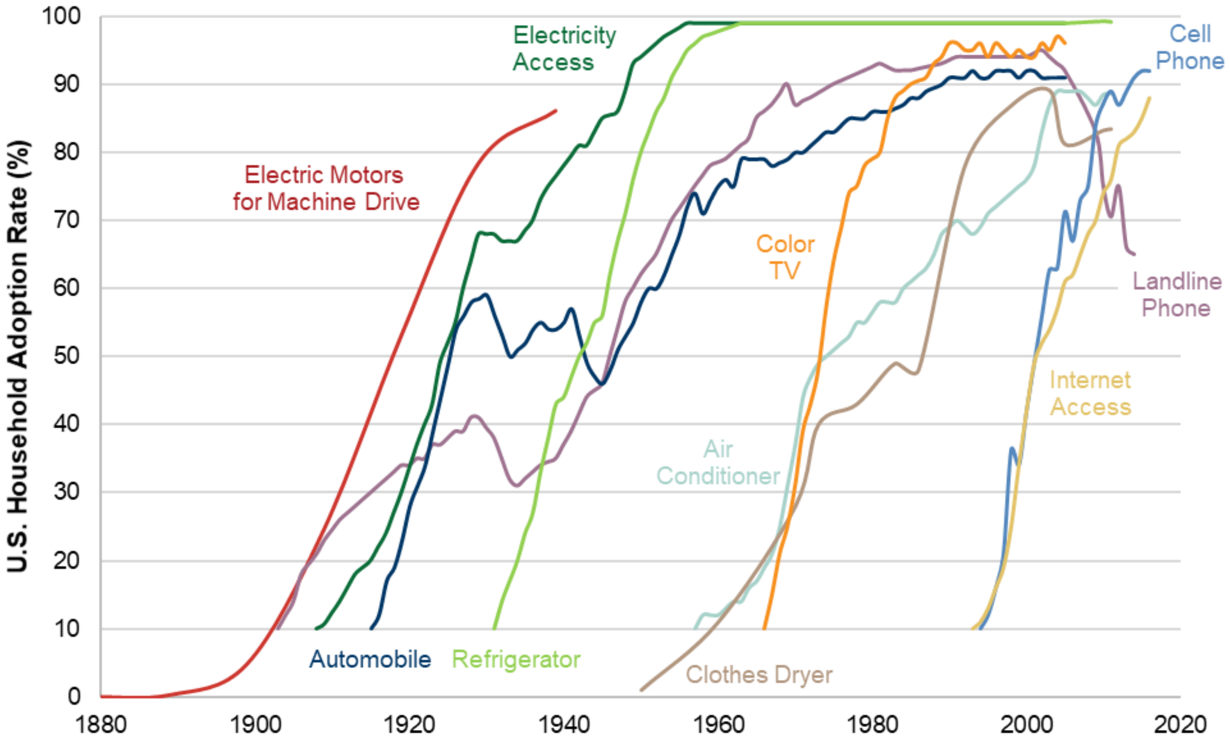

Figure ES-1. Diffusion of various technologies in U.S. households

Data Sources: Du Boff 1964 in Devine 1983 for electric motors; Ritchie and Roser 2018 for all others

The transportation sector experiences the greatest technology transition toward electric vehicles in the scenarios from this study. A representative example of scenario results for one segment of the transportation sector is shown in Figure ES-2, which includes the sales share, vehicle stock, and miles traveled for the light-duty fleet (cars and trucks) in the three scenarios. These estimates foresee ranges of stock penetrations of plug-in electric vehicles in the 2050 light-duty fleet from roughly 11% in the Reference scenario to nearly 84% in the High scenario. More broadly, plug-in hybrid and battery electric vehicles are estimated to grow in all on-road transportation segments in the Medium and High scenarios. In the Medium scenario, growth in plug-in electric vehicles occurs most prevalently for transit buses, throughout the light-duty fleet, and primarily for short-haul applications for medium- and heavy-duty trucks. This expansion is most pervasive in the High scenario, which is designed to include plug-in electric vehicle sales shares beyond many existing studies and where over 240 million light-duty electric cars and trucks, 7 million medium- and heavy-duty electric trucks, and 80,000 electric transit buses are estimated to be on U.S. roads by 2050. For comparison, there were about 560,000 plug-in electric vehicles on U.S. roads by the end of 2016. Together, these electric vehicles would account for up to 76% of vehicle miles traveled in 2050.

The buildings and industrial sectors generally see less potential for transformational change nationwide, but electrification in these sectors could acutely affect certain regions and end uses. Still, a significant increase in building appliance manufacturing and adoption would be needed in our scenarios as the electric devices are found to provide up to 61% of space heating, 52% of water heating, and 94% of cooking services in the combined commercial and residential sectors by 2050 in the High scenario, compared with 17%, 26%, and 34%, respectively, in the Reference scenario. Heat pumps are found to be key technologies for buildings electrification especially in the High scenario in which over 170 million heat pumps are modeled to provide water and space heating (and space cooling) services to residential homes, including those in cold climate regions. The high efficiency and multi-service potential of heat pumps can support their economic attractiveness; however, barriers to heat pump adoption, such as buildings retrofits and consumer familiarity, might limit growth in sales. Aggressive electrification could also lead to adoption of industrial electrotechnologies: 63% of curing needs, 32% of drying services, 56% of other process heating and a range of other industrial end-uses by 2050 would be electrified in the High scenario. Electrotechnologies with productivity benefits have the most potential for industrial electrification, while other technologies without these benefits might find narrower opportunities for adoption. In the body of the report, we describe assumptions that go into the development of all scenarios in the transport, buildings and industrial sectors.

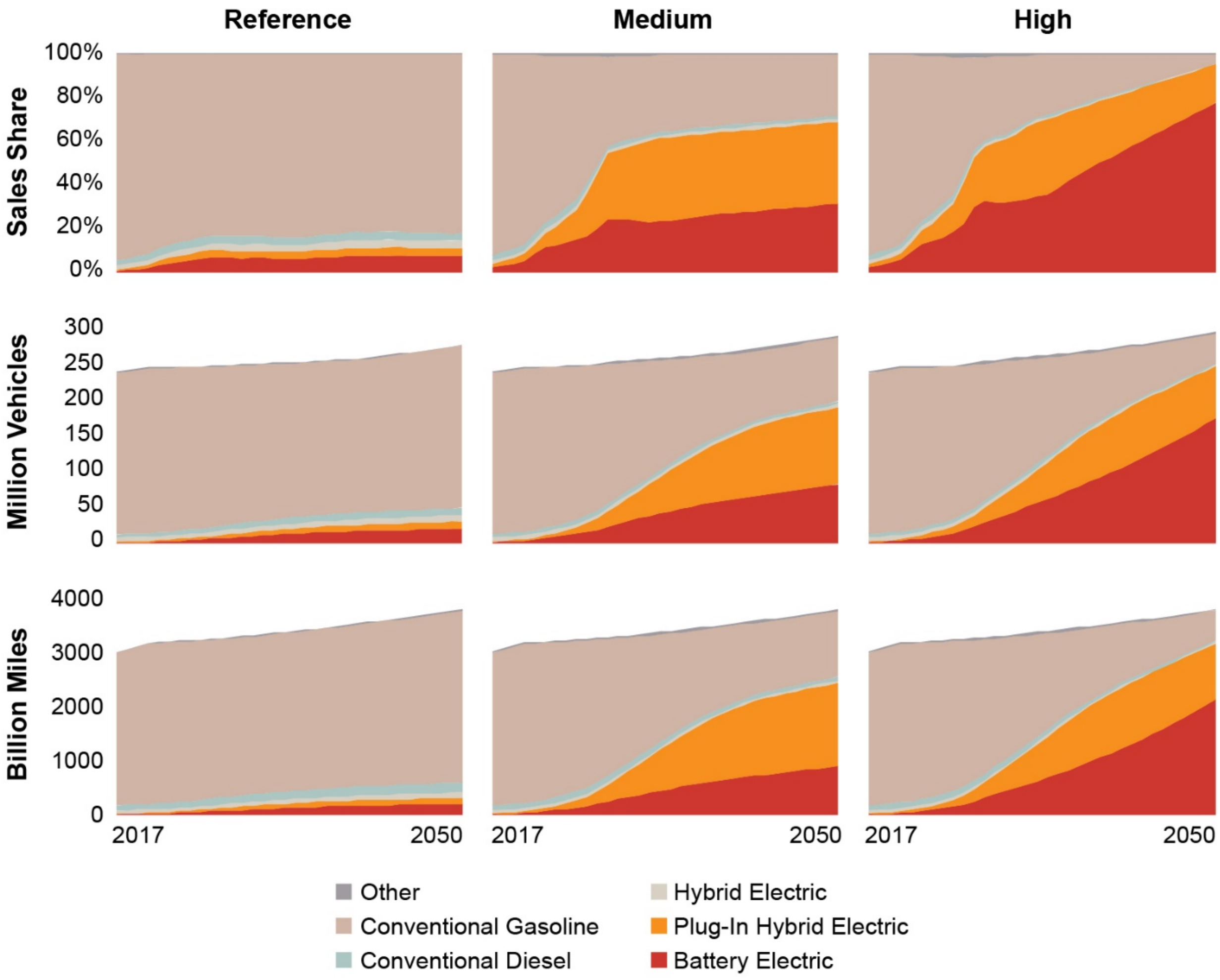

Figure ES-2. Scenarios of light-duty vehicle sales share, stock, and miles traveled

Electrification has the potential to significantly increase overall demand for electricity, although even in the High scenario, compound annual electricity consumption growth rates are below long-term historical growth rates. The Reference scenario has the most limited impacts from electrification, but continued growth in both population and the U.S. economy leads to a compound annual growth rate (from 2016 to 2050) in electricity demand of 0.65% and 4,722 terawatt-hours (TWh) of total consumption by 2050. In the Medium and High scenarios, total 2050 electricity demand is estimated to be 934 TWh (20%) and 1,782 TWh (38%) greater, respectively, than in the Reference. Compound annual growth rates are found to be 1.2% and 1.6% in these scenarios, respectively. These growth rates are well below the historical rate from 1950 to 2016 (4%/yr) and fall below the 1.8%/yr growth rate observed over the same duration (34 years, 1982–2016) as the study future period. However, comparing absolute year-to-year changes in consumption (rather than compound annual growth rates) in the scenarios shows how widespread electrification can lead to historically unprecedented growth. In the High scenario, the average increase (during 2016–2050) in annual electricity consumption is about 80 TWh/yr, compared with 50–55 TWh/year over the prior 34 years. The vast majority of this increase occurs in the transportation sector. Buildings electrification leads to more-limited incremental growth in annual electricity consumption in part because of the high efficiency of heat pumps and their partial displacement of inefficient electric resistance heaters. Figure ES-3 summarizes annual electricity consumption results in these scenarios, which use a central Moderate technology advancement projection. The report and accompanying data include additional results for other technology projections modeled.

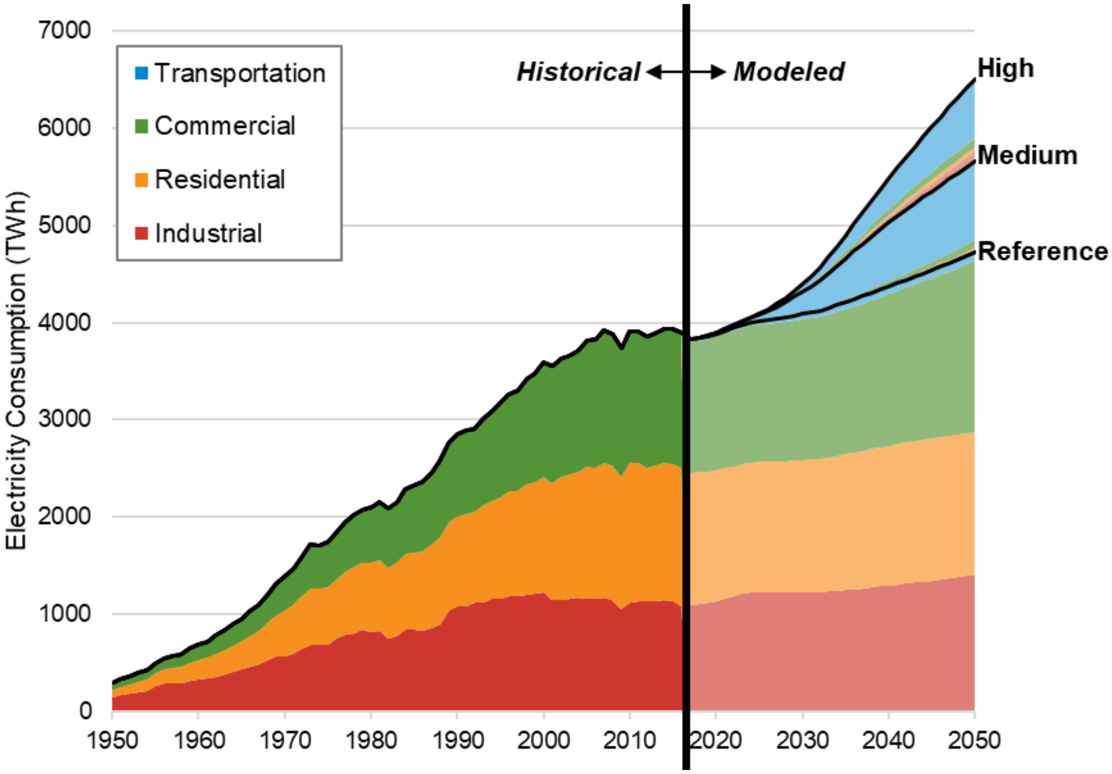

Figure ES-3. Historical and projected annual electricity consumption

Moderate technology advancements are shown. Slight adjustments were made to the modeled industry consumption estimates (for 2017-–2020) to align them with available historical data.

In addition to growth in annual electricity consumption—driven to a large degree by greater adoption of plug-in electric vehicles—electrification has the potential to significantly shift load shapes, particularly due to increased reliance on electric heat pumps for space and water heating needs. Figure ES-4 shows how peak demand grows and shifts to the winter season for a substantial number of states in the High scenario. The size of the pie charts corresponds to the magnitude of the highest estimated hourly load for each state, and the pie wedges show how the top 100 load hours are distributed across the four seasons. In 2015, all states excluding those in or near the Pacific Northwest are estimated to be primarily summer peaking, with a majority of the top 100 load hours falling in June, July, or August. Under the Medium and High electrification scenarios, growth in winter electricity consumption outpaces consumption in non-winter months in many regions, in large part because of greater adoption of electric air source heat pumps in the Midwest and Northeast regions, which have colder climates. Along with the shift in when peak demand occurs, the size of the peak also increases. The aggregate and coincident peak national hourly demand in 2050 is estimated to be 19% and 33% greater in the Medium and High scenario, respectively, than in the Reference scenario, where peak demand is estimated to reach 838 gigawatts (GW) in 2050. While transportation electrification has an outsized impact on annual electricity consumption compared with the other sectors, buildings electrification can dramatically change the characteristics of peak demand. Changes to peak load, and shifts to load shapes more generally, can be sensitive to the degree of demand-side flexibility, which we include in our modeling but only to a limited extent. Further research is needed on this important topic. How electrification impacts load shapes could have significant impact on electric utility planning, grid operations, reliability assessments, and electricity markets.

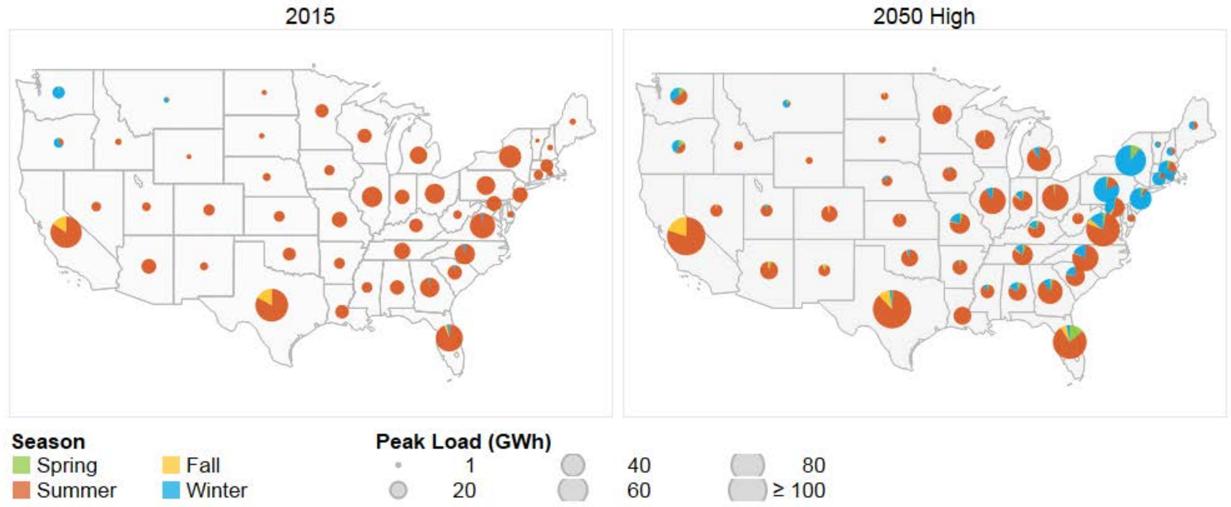

Figure ES-4. Estimated peak load magnitude and seasonal timing by state for 2015 (left) and 2050 in the High scenario (right)

The size of the pie charts corresponds with total electricity demand (GW) during the top demand hour. The pie wedges show the seasonal distribution of the top 100 hours with the highest demand by state. Seasons are defined along monthly groupings: summer includes June, July, and August; fall includes September, October, and November; winter includes December, January, and February; and spring includes March, April, and May. Data shown, including 2015 data, are based on modeled estimates.

Widespread end-use electric technology adoption would result in substantial shifts in fuel, electricity, and total energy consumption. In 2050, electricity's share (of total final energy) increases to 32% in the Medium and 41% in the High scenario—significantly above the 23% in the Reference scenario and 19% in 2016 (Figure ES-5). The impacts to electricity share vary significantly by sector, with the largest growth found in transportation for the Medium and High scenarios and the least change occurring in industry. Consistent with observed trends since 1950 the buildings sectors remain the most electrified in all scenarios and with growing electricity shares of final energy. For example, the commercial buildings sector is nearly 75% electric under the High scenario. Electrification would also lead to reduced use of gasoline, diesel, and natural gas fuel. Demand-side fuel use reductions of 74% gasoline, 35% diesel, and 37% natural gas in 2050 are found in the High scenario, relative to the Reference. It is possible that some of the reduced on-site natural gas use would be offset by greater gas-fired generation, which will be studied in a future EFS report. Similarly, reductions in petroleum-based fuels could lead to greater energy export opportunities and these changes in fuel use could have important impacts on global energy markets, energy security, and geopolitics. Finally, advanced electric technologies are often more energy efficient than competing options that provide the same end-use services. This greater energy efficiency resulted in 13% reduction in 2050 final energy consumption in the Medium scenario, relative to the Reference, and 21% in the High scenario. This higher overall efficiency of electric technologies is one reason that power demand does not grow even faster.

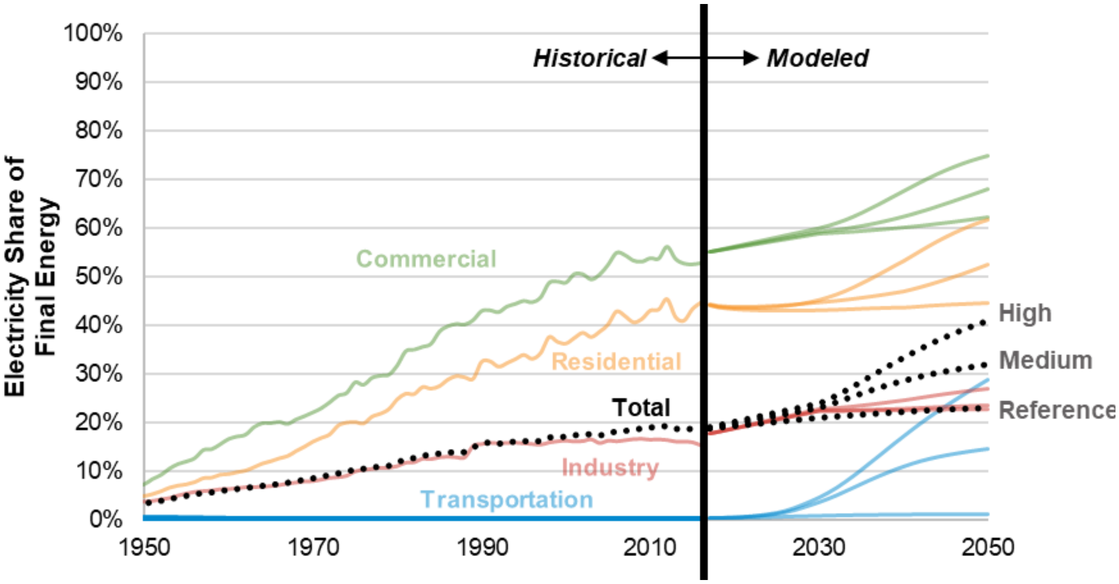

Figure ES-5. Electricity share of final energy consumption

Moderate technology advancements are shown. Historical and modeled data have slightly different scope and therefore are not fully comparable. Notably, modeled data omits fossil fuel extraction and refining. However, differences amount to only a few percentage points between the 2016 historical data and the 2017 modeled data. Visual adjustments and interpolations were used for the modeled data (for 2017—2030) in the figure shown.

Forward-Looking Opportunities

Results from this study point to several follow-on activities that could add further value to our understanding of electrification potential, challenges, and impacts. These are focused only on the scope of material covered in this report (the demand side), and do not necessarily represent an integrated electrification strategy of forward-looking opportunities. Identified key areas that are ripe for additional research and analysis include:

- **Analysts need improved methods to assess the dynamic world of end-use technologies.** Understanding the technology improvements needed and advancement possibilities for a comprehensive set of end-use options is critical to both assess future competitiveness as well as to inform R&D decisions. Furthermore, the potential for disruptive change in batteries and charging technology, for example, is significant and could have a far-reaching impact on electrification of the transport sector around the world. Similarly, the potential for autonomous vehicles, likely electrified, could have a major impact on the number of vehicles in operation, vehicle miles traveled, and related infrastructure needs. Similar adoption of “smart” and “grid-connected” appliances and equipment could impact the amount and timing of energy use in buildings and industry.

- **Advanced consumer choice models for many end-use technologies are needed to deliver insights on the drivers of electric technology adoption.** Although an increasing number of such models have been developed—including an adoption model for the light-duty vehicle fleet used in the present report—sophisticated models that capture not only economic trade-offs between technologies but also consumer preference and behavior, supply chain and infrastructure impacts, risk, financing, and integrated challenges and opportunities across technology portfolios remain at early stages of development. Detailed and accurate consumer choice models could help inform policymakers; guide R&D strategies to lower costs and improved desirability; and motivate engineering design to influence appropriate adoption.

- **Improved data collection and modeling in the industrial sector are needed to better understand the potential and impact of industrial electrotechnologies.** Although this report advances the level of understanding related to electrification for a subset of industrial activities, the research community would benefit from a more granular understanding of the potential for process-level activities to be electrified. This includes identification, quantification, and recognition of the productivity benefits of electrotechnologies.

- **A better understanding of the potential impacts of electrification on load shapes and opportunities to influence them is critical to minimizing overall costs.** Future reports in this series should help add new knowledge on this subject, but policy-related questions in electricity markets and utility planning—especially as they relate to the demand side’s participation in such areas—will remain an important area for ongoing study.[4] Furthermore, a better understanding of consumer acceptance, behavior, and participation in demand response and demand-side flexibility, enabled in part by electrification, is a key research area.

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[4] As part of the EFS, we have developed a new more-detailed model of electricity consumption, referred to as demand-side grid (dsgrid), that can be used to tackle this research topic. The model documentation (Hale et al. forthcoming) is one of the reports in the EFS series.

- **A deeper understanding of related non-technical and system factors could inform planning and deployment.** While this study focused attention on technology diffusion—including adoption, device lifetime, fleet turnover rates, and related issues—to better understand the potential for transformation due to electrification, a more comprehensive set of road mapping exercises would help to understand key market, policy, technology, and institutional needs at the national, state and/or local level. These might relate to efficient deployment of vehicle charging infrastructure, tariff design for smart vehicle charging and heat pump usage, building codes to further enable electrification, and coordinated R&D strategies for key end-use technologies.

Conclusions

The scenarios presented in this report are used to characterize changes to end-use sectors under futures with increased electrification and to quantify how those changes might impact the amount and shape of electricity consumption. These scenarios were developed primarily using expert judgment and an energy system accounting framework. Of course, technology adoption will ultimately depend on a set of complex considerations that are not fully assessed using our methodology, but which are discussed extensively throughout the report. These interacting factors include technology and fuel cost trade-offs, infrastructure needs, environmental policies, and consumer preference. Within each of these factors are barriers that might challenge increased electrification—such as higher upfront costs or unfamiliarity with new electric technologies—but also opportunities that could yield greater adoption—such as increased productivity or expanded value streams enabled by electric and/or grid-connected technologies. Understanding and quantifying these factors are needed to both evaluate the implications of a potential increased electrification future and to influence the degree of future electrification. Overall, this report represents an initial step to inform researchers and decision-makers with data and context to plan for a potential future in which electricity powers an expanded share of the U.S. energy economy.

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1 Introduction

Over the past century, electricity has played an increasingly important role in the U.S. energy system and the daily lives of nearly all Americans. It has helped drive innovation and economic growth, enable technology innovations, deliver health and social benefits, and improve quality of life and promote convenience in everyday lives. The functioning of modern societies is fueled by this ubiquitous, yet invisible, energy carrier. The reliance on electricity is expected to grow even more in the future. However, electricity production—as with any source or carrier of energy—has also created negative impacts to public health, the environment, and the economy at local, national, and global levels. The implications of increased electricity consumption and production will be tied to the evolution and operation of the future U.S. electricity system. The Electrification Futures Study (EFS)—a multi-year research effort—is designed to explore these complex topics.

Specifically, the EFS uses a scenario analysis approach to prospectively model and assess electricity demand levels and load patterns, power sector operations and evolution, and the potential costs and impacts of increasing electrification in the United States. In this report, which represents one of multiple research products within the EFS, we present demand-side scenarios of electric technology adoption and U.S. electricity consumption through 2050. Other published EFS reports focus on projections of end-use electric technology cost and performance projections (Jadun et al. 2017) and new modeling capabilities (Hale et al. forthcoming) to be used in the EFS. And, supply-side projections and impact assessments of the scenarios will be examined in future EFS reports.

U.S. electricity consumption has continuously evolved ever since the construction of the first central power plants and electrical grids in the late 1800s. Numerous and complex drivers have caused these changes since that time, including economic growth, population growth, technology change, behavioral change, fuel price and other supply-side shifts, and policies. In Section 2, we summarize the history of U.S. electricity consumption and its historical drivers. In Section 3, we present the literature on past energy and technology transitions.

In this report and in the broader EFS, we focus our analysis exclusively on the potential impacts of one possible driver and what could be classified as an energy transition: electrification. For our purposes, electrification is defined as the substitution of electricity for direct combustion of non-electricity-based fuels (e.g., gasoline and natural gas) used to provide similar services. Our fuel switching-based definition includes any potential growth in the service driven by population or economic change. The definition does not include new or emerging energy services driven by technological or economic change, such as indoor agriculture, new plug loads, and expansion of data centers. In other words, our analysis focuses on electric technologies that can be used to replace existing non-electric ones—e.g., electric vehicles for internal combustion engine vehicles, heat pumps for natural gas space heating, and electric induction furnaces for fuel-fired industrial furnaces—and *not* on yet to-be-developed electric-based technologies.[5]

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[5] We consider a range of future advancement projections of existing end-use electric technologies, including projections that imply significant improvements from current commercially available ones.

Motivations for studying electrification are numerous. First, new electric alternatives are emerging in areas that have traditionally been dominated by non-electric technologies. Light-duty transportation is an example where this is occurring: in 2016, U.S. plug-in electric car registrations totaled 160,000 compared with only about 1,000 new registrations in 2010, and a growing proliferation of EV options are planned by major automobile and freight vehicle manufacturers, with both resulting from technology advancements and in response to various policies (IEA 2017).[6] Another example is in residential buildings where, from 1979 to 2012, the share of new homes built with an air source heat pump (ASHP) grew from 17% to 49% for U.S. multifamily homes and from 25% to 38% for single-family homes (Lapsa and Khowailed 2014). Anecdotal evidence suggests ASHP sales have increased even more since then, although they often replace (or would otherwise take the place of) electric resistance heaters, so the amount of electrification is more muted.

A second motivation for exploring electrification is the potential externality benefits of electrification, including security and environmental benefits. As electricity relies almost entirely on domestic generators and fuels in the contiguous United States, electrification may increase energy security. Recent studies[7] also identify electrification as key component of pathways to reducing greenhouse gas emissions. A related benefit is the overall higher energy efficiency of electric technologies, which could—all else being equal—reduce the negative impacts of energy use. However, the efficiency and environmental benefits of electrification ultimately depend on sources used to generate electricity. How electricity supply might evolve to meet new electric loads and their impacts will be examined in future EFS reports.

On a local level, electrification is being investigated or even experimented with to help improve air quality and the consequential health benefits. Many existing local actions target high-congestion and high-polluting regions, such as marine ports and airports (e.g., Port of Long Beach and The Port of Los Angeles; NEEP 2017a; NREL 2017). Expanding interest in electrification from state and localities could motivate widespread electrification from the ground up to the national scale.

Another motivation for studying electrification is to inform utility planning, including integrated resource planning and infrastructure development processes within the electric utilities across the nation to help with their grid modernization efforts. These efforts rely on forecasts of electricity consumption and sales over several decades, and electrification could influence these forecasts and thereby impact policies and planning at the utility, state, and national levels. For example, electrification has been found to potentially impact anticipated utility sales and plant profitability, which would subsequently impact electric industry business strategies (Weiss et al. 2017; EEI 2014). In particular, electrification could reverse the declining or flat demand growth trend since the mid-2000s. The Electric Power Research Institute's Efficient Electrification Initiative, including a recent technical study—*U.S. National Electrification Assessment* (EPRI 2018)—

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[6] Initial estimates indicate 2017 sales might reach nearly 200,000 PEVs ("December 2017 Plug-In Electric Vehicle Sales Report Card," insideevs.com, Last updated January 4, 2018, https://insideevs.com/december-2017-plugin-electric-vehicle-sales-report-card/).

[7] Williams et al. 2012; Williams et al. 2014; Alexander et al. 2015; Wei et al. 2013; White House 2016; Steinberg et al. 2017; Iyer et al. 2017

provides another example of interest in electrification by the utility industry and its research partners.

These motivations and the possibility for widespread electrification warrant further detailed research into the potential impacts on the U.S. energy system. In this report, we apply a scenario analysis approach wherein multiple future electrification projections—electric technology adoption and resulting electricity consumption projections—are posited and evaluated. We note that none of the scenarios reflects a prediction nor are the scenarios designed to achieve a specific goal. Instead, they are intended to represent plausible futures where electrification increases beyond current levels as a basis for evaluating the impacts of electrification. [8] Unlike other studies (e.g., White House 2016; Iyer et al. 2017) where energy-economic modeling is used to assess the uptake of electric technologies based on assumed costs and policies (e.g., emission reduction requirements), our analysis relies on an accounting framework where technology adoption is exogenous to the modeling. We acknowledge our approach has its limitations, although our assessment employs high-fidelity tools and models that include more-detailed technological, spatial, and temporal resolution than those used in many existing studies. In addition, any adoption results from consumer choice modeling over a multi-decade span would need to recognize significant long-term uncertainties in technology, market, policy, and behavioral conditions. Our scenario development is designed to capture a wide range of these uncertainties through the use of multiple technology adoption and cost sensitivities. Overall, we do not intend to suggest that electrification is likely or desirable; however, whether it is beneficial (and to whom) will be informed to some extent by the broader EFS analysis.

In the EFS, we consider only the expansion of direct end-use electric technologies. Other studies[9] have analyzed scenarios that include expansion of alternative energy sources and energy carriers—such as hydrogen-based technologies, power-to-gas, or direct biomass combustion—but this analysis focuses only on direct electric technologies. The scope is in part driven by our broader analysis focus on the electricity system.[10] We consider electrification in all major sectors—transportation, buildings, and industry—but examine only select end-use services within each due to data and modeling limitations. Table 1.1 shows the scope of our electrification analysis.

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[8] Melaina et al. (2016) provide another example of national-scale analysis on the public and private impacts of electrification using a scenario analysis, but it is limited in scope to light-duty electric vehicles only.

[9] We present and summarize a collection of existing studies that explore these alternative energy sources and carriers in Appendix A.

[10] Active research on widespread expansion of other energy sources and carriers (e.g., DOE’s H2@scale initiative, https://energy.gov/eere/fuelcells/h2-scale) exists, and future research needs include considering a more-complete set of future energy scenarios.

Table 1.1. Scope of Electrification in the EFS Scenarios by Sector

Electrified in the EFS Scenarios		
Transportation Sector	**Buildings Sector**	**Industrial Sector**
Light-duty passenger cars and trucks Commercial light trucks (medium-duty vehicles) Freight trucks (heavy-duty vehicles) Transit buses	Space heating Space cooling Water heating Cooking Clothes drying	Space heating Machine drives Process heating in primary metals, transportation equipment, glass, bulk chemicals, and other manufacturing Curing & drying in printing, wood products, and plastic and rubber products Boilers
No Additional Electrification in the EFS Scenarios		
Transportation Sector	**Buildings Sector**	**Industrial Sector**
Off-road Vehicles Air Marine Rail Pipeline	Other (e.g., outdoor cooking and lawn equipment)	Blast furnace/basic oxygen furnace steelmaking Combined heat and power Pulp and paper Petroleum refining Cement and lime Mining Construction

Although our analysis does not comprehensively consider electrification of all end uses, electrification opportunities modeled in our scenarios cover a significant fraction of total energy consumption. For example, data shown in Figure 1.1 (next page) indicate that all end uses considered for electrification comprised 74%[11] of 2015 total primary energy consumption[12] and about 79% of 2015 energy-related CO_2 emissions. Our analysis also focuses on end-use services that have the potential for significant increase in electrification (see also Figure 1.1), such as on-road transportation, residential and commercial space and water heating, and multiple industrial activities. Important areas requiring sizable energy consumption relative to total U.S. energy use, but where we are not considering additional electrification, include aviation and other non-road transportation, petroleum refining, mining, and other industrial process.[13] These omissions do not imply that electrification opportunities are not viable in these areas.[14] Moreover, the relative importance of these may grow over time in terms of energy consumption and emissions.[15] Thus, future research is warranted to investigate electrification possibilities and impacts beyond the scope of our analysis.

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[11] Industry electrification potential is based on the ratio of energy end-uses considered for electrification from the 2014 Manufacturing Energy Consumption Survey to the total 2014 energy use from AEO 2015.

[12] *Primary* energy is the raw amount of energy available before any conversion processes are performed. Conversion processes transform the raw energy either into useful work or to one or multiple energy carriers. In contrast, *final* energy is the amount of energy used on-site only. Conversion processes include losses, such as waste heat in combustion, and therefore final energy use is necessarily lower than primary energy consumption. Here, we report data from the EIA, which uses a “fossil-fuel equivalency” approach to calculate primary energy from noncombustible renewable fuels. In this report, we focus on end-use energy consumption only (and not total energy production), and we therefore do not report primary energy results. The EIA *Annual Energy Review 2011* (EIA 2011, Appendix F) provides a discussion of their approach and alternatives. See also Donohoo-Vallett (2016) for a discussion of different energy accounting approaches.

[13] The incomplete scope of electrification considered is due to several limitations related to data and tools, and it does not necessarily reflect a lack of electrification opportunities. For example, limitations with industrial energy data significantly narrowed the range of subsectors examined. As described in Section 5, our analysis of industry occurs at the energy end-use level (e.g., process heating; facility heating, ventilation, and air conditioning (HVAC); machine drive; conventional boiler use; or other non-process use) and not at the process- or technology-level, which would require additional detailed data and analysis tools that do not yet exist for the U.S. industrial sector. The ultimate basis of energy end-use data is the Manufacturing Energy Consumption Survey (MECS 2017), which excludes the agriculture, construction, and mining industries. Although we were able to obtain some end use data from the AEO, we did not include construction and mining industries in our analysis despite known electrification opportunities (e.g., GE Transportation 2018). EIA’s recent advancements to the NEMS Industrial Demand Module (IDM) have introduced process-level detail for the iron and steel, aluminum, pulp and paper, glass, cement, and lime industries (EIA 2018). However, this process-level detail is incompatible in many circumstances with our chosen analysis tool, EnergyPATHWAYS, particularly for the iron and steel sector. Other industries were excluded from our analysis based on their level of process complexity and integration (petroleum refining), insufficiently mature electrotechnologies (process heating in cement and lime; see Philibert 2017 for an identification and discussion of these technologies), reliance on process byproduct combustion (pulp and paper), or general lack of identified electrification opportunities (c.f. Jadun et al. 2017). Similar limitations exist for non-industrial sectors, such as aviation and outdoor cooking.

[14] EPRI (2017) and Birky et. al (2017) provide examples of non-road transport electrification options.

[15] For example, EIA (2017c) projects energy-related CO2 emissions from on-road vehicles to decrease in relative terms, falling from 82% of total transportation emission in 2015 to 71% in 2050.

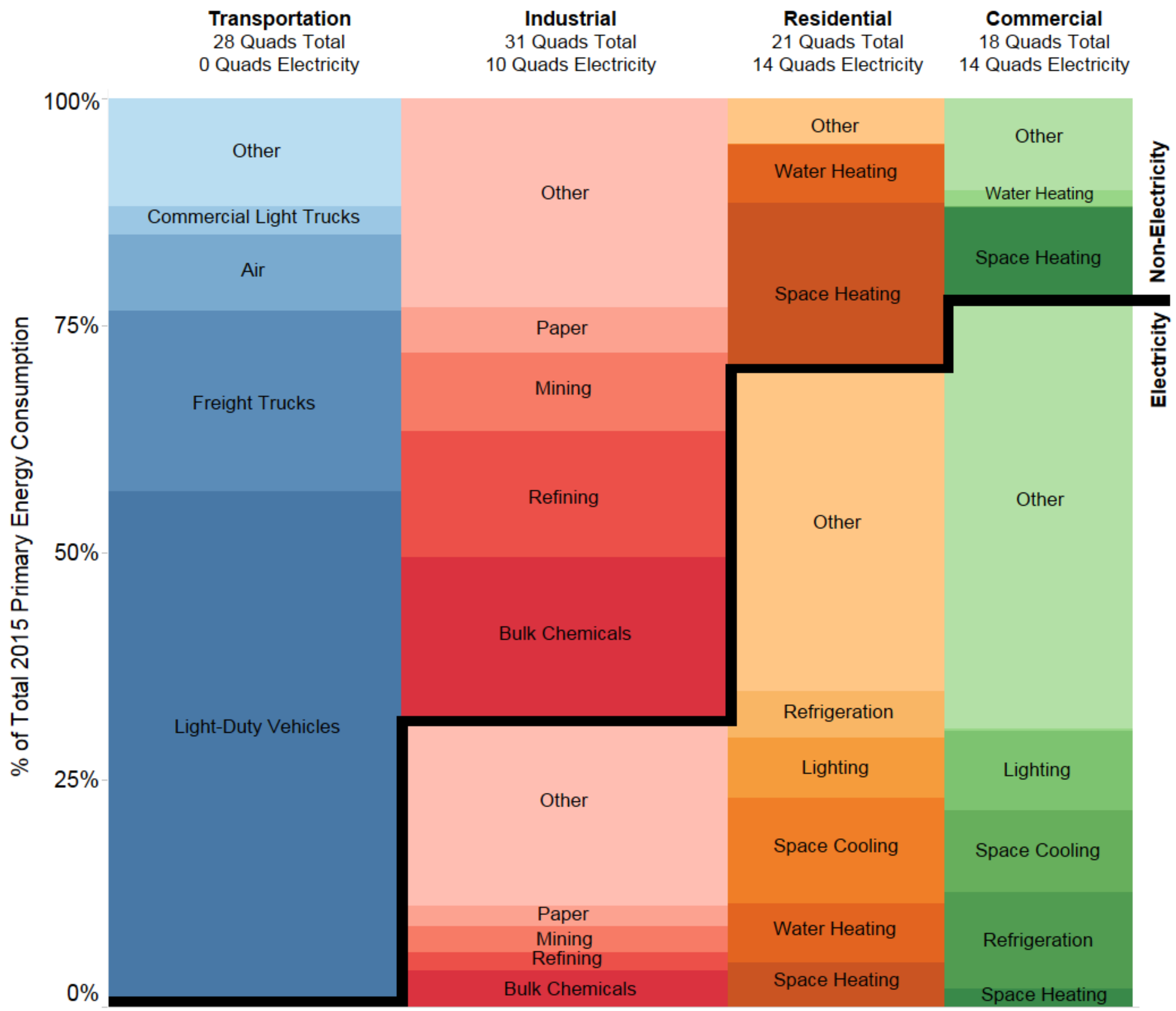

Figure 1.1. Primary energy consumption shares in 2015

Data from EIA 2017c; Figure from Jadun et al. 2017

Total sectoral energy use 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 (below bold line) and from non-electric energy use (above bold line). 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 one quad) is not shown because of its relative size.

We evaluate electrification scenarios for the contiguous United States through 2050. Results are presented primarily at the national level, although select regional examples are also included. Additional data, including state-level scenario data, are available at www.nrel.gov/efs. In this report, we present the demand-side scenarios only; future reports in the EFS series will include supply-side scenarios.[16] Section 4 provides detail on the scenario design and analysis scope. Section 5 describes our methodology. We present our scenario results in Sections 6 (end-use equipment sales and stock) and 7 (electricity consumption results). Finally, we present a list of our key findings and future work in Section 8.

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[16] We treat distributed generation (e.g., rooftop photovoltaics) on the supply side and, therefore, distributed generation is not presented in this report.

2 A History of U.S. Electricity Consumption

Although the EFS and this report focus on future electrification and electricity consumption scenarios, historical changes in electrification and U.S. electricity consumption provide valuable context for the future projections. Figure 2.1 shows the numerous changes in electricity consumption in the residential, commercial, industrial, and transportation sectors since the middle of the 20th century. During this period, growth in annual electricity consumption was similar in the commercial and residential sectors, as total consumption increased by a factor of 20 over the 66 years shown. Industrial electricity consumption increased only 8.5x over the same period, while transportation-related electricity consumption remained negligible relative to the other sectors. Overall, the historical data show a general long-term trend of increasing absolute total electricity consumption (from about 300 terawatt-hours [TWh] in 1950 to nearly 4,000 TWh in 2016) but decreasing consumption growth rates, albeit with significant year-to-year fluctuations. Figure 2.1 shows how the (five-year trailing) compound annual growth rate (CAGR) exceeded 10% per year in the 1950s but dropped to about zero during the last decade. The CAGR over the full 66-year period shown (from 1950 to 2016) is 4% per year.

In the buildings sectors, electricity consumption growth has been historically driven by population expansion, economic growth, and land-use development patterns (e.g., urbanization) which create increased demand for services (e.g., lighting, heating, and cooling), in combination with the advancement and adoption of electric technologies, such as air conditioners, refrigerators, and televisions (Brown and Koomey 2003). In the past few decades, the spread of computers, office equipment, and consumer electronics has grown to be an increasing portion of electricity consumption (DOE 2015). Significant efficiency improvements in lighting, building insulation, and other areas have occurred over this period as well, causing the growth of electricity consumption in buildings to slow, particularly over the most recent decade.

Electricity consumption in industry has a complex history. Steady growth from the years shortly after World War II through the 1970s was driven by population and economic expansion, which in turn drove increased production across a wide range of industries. A continued move toward electric machine drives (e.g., electric motors, pumps, and fans) during the early part of this period, as well as the growth of electricity-intensive processes, drove greater industrial electricity consumption (Boyd, Hanson, and Sterner 1988). From the early-1980s to the present, electricity consumption (and electricity's share of final energy consumption) in industry has remained flat or declined. Reasons for this include within-sector structural changes, technology transitions, fuel supply and price considerations, and energy intensity improvements (Croner and Frankovic 2018; Belzer 2014; Boyd and Roop 2004).[17]

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[17] Trends in the electricity intensity of manufacturing have been found to be markedly different from trends in fuel use since 1970. Using a Divisia index decomposition, Belzer (2014) estimated that from 1970 to 1985 manufacturing electricity intensity remained relatively constant while fuel intensity decreased by more than 30%. The most recent decomposition analysis of electricity use by U.S. manufacturers estimated that the reduction in electricity intensity during the 1990s was due in equal parts to structural change and improvements in intensity (Boyd and Roop 2004).

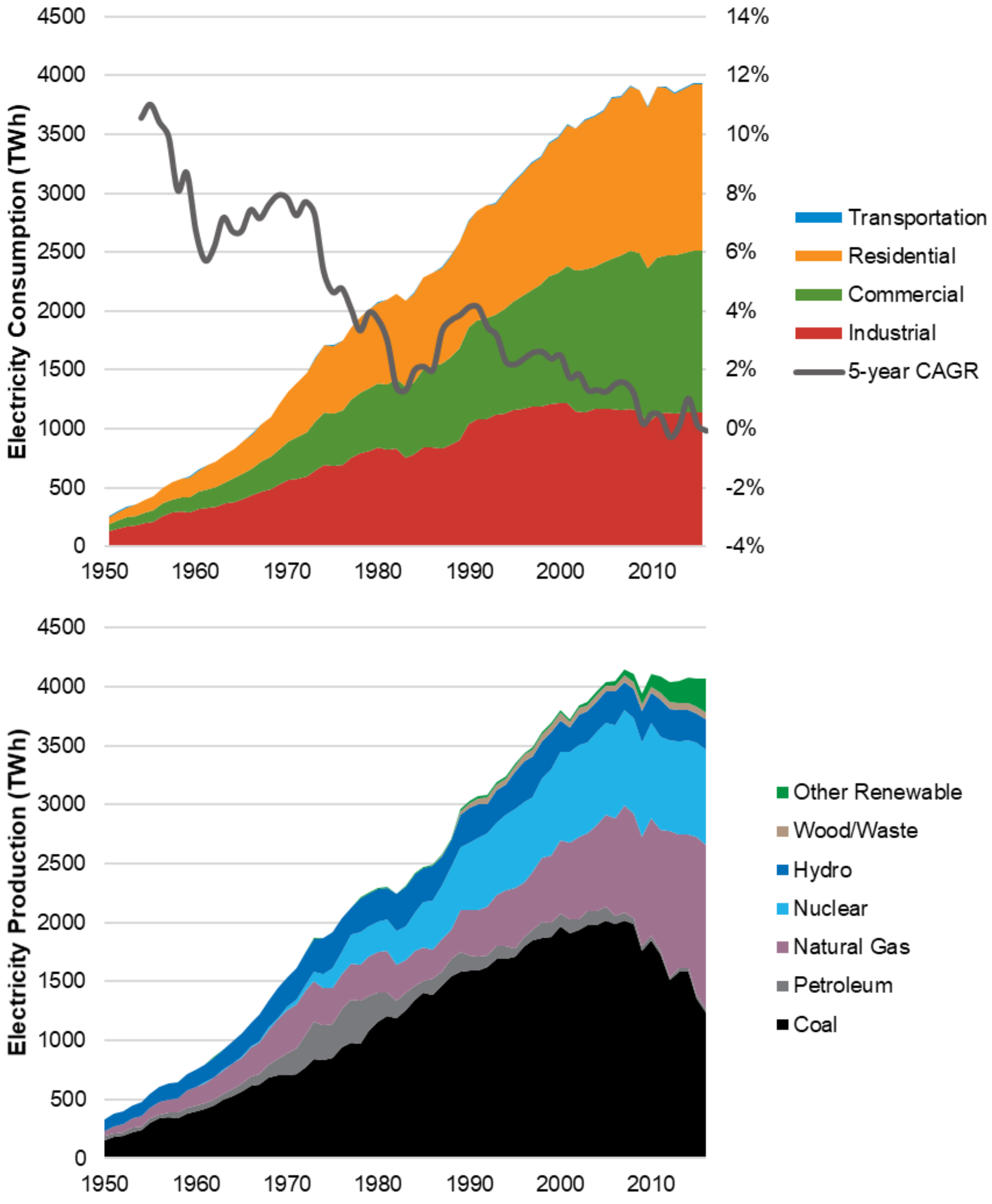

Figure 2.1. History of U.S. electricity consumption (top) and production (bottom)

Data from EIA Annual Energy Review (EIA 2011) and EIA Monthly Energy Review (EIA n.d.)

For consumption, data attribution to each sector is from the U.S. Energy Information Administration (EIA), which may include behind-the-meter plug-in electric vehicle charging in the residential and commercial sectors. Starting in 1989, the consumption data also include net self-generation of electricity from renewable sources (except geothermal) and combustible fuels. The consumption data include EIA estimates of behind-the-meter solar generation based on estimated growth rates from the Annual Energy Outlook. The consumption chart includes a five-year trailing CAGR of the total electricity production.

As is apparent from Figure 2.1, electricity consumption in the transportation sector is significantly smaller than it is in the other sectors in all years. In fact, total electricity consumption in the transportation sector decreased during the 1950s due to declining usage of electricity-fueled public transit and passenger rail as suburbs developed and petroleum-based on-road vehicle usage became more prevalent (Yago 1984; Glaeser and Kohlhase 2004). In the 1980s, transportation-related electricity consumption began to increase in absolute terms, but it remained minute compared with other sectors. The portion of electricity dedicated to transportation decreased from over 2% to 0.5% during the 1950s, then from 0.5% to 0.15% during 1960–1980, and it has remained close to 0.2% since 1980. In very recent years, an increase in plug-in electric vehicles (PEVs) sales has resulted in an increase in transportation electricity consumption, but the still small share of PEVs on U.S. roads has yet to have any material impact on transport-related electricity demand at the national level. Additionally, separating the electricity consumption of PEVs charged at home or work from the rest of the electricity consumption in the residential and commercial buildings sectors will create difficulties in measuring electricity consumption in the transportation sector in the future.

Because changes in electricity consumption will impact fuel consumption and emissions, Figure 1 also shows historical trends in the fuel mix for electricity generation (bottom). A few significant recent trends in the electricity supply include the growth of solar and wind, stagnant quantities of nuclear and hydroelectric, growth of natural gas, and decrease of coal. We present the historical generation data for background context, as we focus on only the demand-side in the analysis. Planned reports in the EFS will examine future electricity supply.

Figure 2.2 shows the share of electricity as a percentage of final (left) and primary (right) energy consumption for the United States in total as well as for each sector.[18] For the primary energy graph, the electricity share includes all the primary energy dedicated to the electricity sector. The allocation of primary energy (and losses) to each sector is proportionally based on the share of annual final electricity consumption in each sector. The trends from Figure 2.2 place the history of electricity consumption in context with total energy use, thus indicating the level of electrification. In 2016, electricity comprised about 19% of final energy and 39% of primary energy consumption, as it increased significantly and relatively steadily from 3% and 14%, respectively, in the mid-20th century. These trends show how much electrification has already occurred, but they also indicate how much energy consumption is not currently electrified and that the amount of electrification and the potential for future electrification vary substantially by sector. For example, the residential and commercial sector data demonstrate consistent growth in the amount of electrification throughout the period, while the industrial sector electrification began to plateau in the early 1980s and very little transportation electrification has occurred to date.

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[18] See Footnote 12 for an explanation of differences between *final* and *primary* energy.

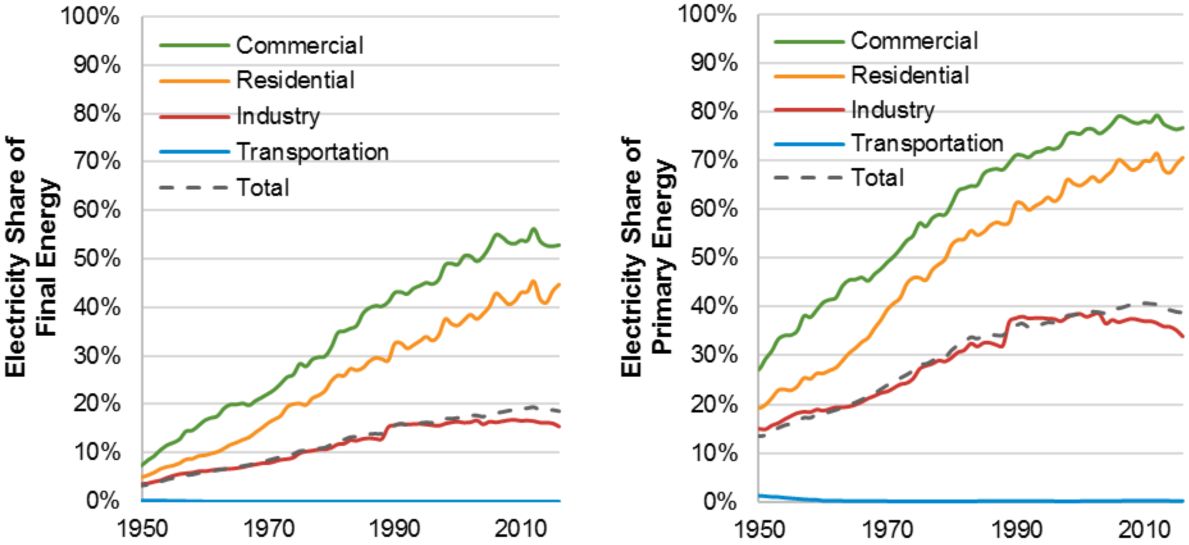

Figure 2.2. U.S. electricity share of energy consumption (1950–2016)

Data from EIA Annual Energy Review (EIA 2011) and EIA Monthly Energy Review (EIA n.d.)

Primary energy for renewable sources follows the EIA custom of multiplying the electricity generation by the average fossil fuel heat rate. Final energy is determined by subtracting the listed electrical losses and the losses associated with the heat rate conversion of renewable production from the sectoral total energy consumption. Losses associated with self-generation of electricity in combined heat and power plants are taken from EIA estimates.

To further place the evolution of electricity consumption within the context of other changes in the U.S. economy, we present nine U.S. energy and economic indicators from 1950 to 2016 in Figure 2.3: total energy consumption, electricity consumption, summer electrical capacity, total energy sector CO_2 emissions, gross domestic product (GDP), population, road vehicle miles traveled (VMT), combined residential and commercial building square footage, and the Federal Reserve index of industrial production. All indicators are indexed to 1980 values. Subsets of these data are shown in Figure 2.4 and are further normalized by population (left) and GDP (right) before being indexed to 1980.

Figure 2.3 shows that, over most of the period shown, all indicators increase over time, which is not surprising given the expanding U.S. economy and population. Interestingly, the figures together also show that a variety of service indicators, namely building sizes and VMT, have increased in absolute terms and on a per capita basis over the entire period, which suggests an increase in quality of life. In contrast, energy consumption per capita peaked in the late 1970s, and both energy and electricity consumption have been generally decreasing—especially per person—since about 2000. Together, these data demonstrate that continued growth in energy services and economic activity have not relied on the commensurate growth in energy or electricity consumption, due to a variety of factors that include economic sectoral shifts and energy efficiency improvements (Belzer 2014; Huntington 2010; Bowden and Payne 2009).

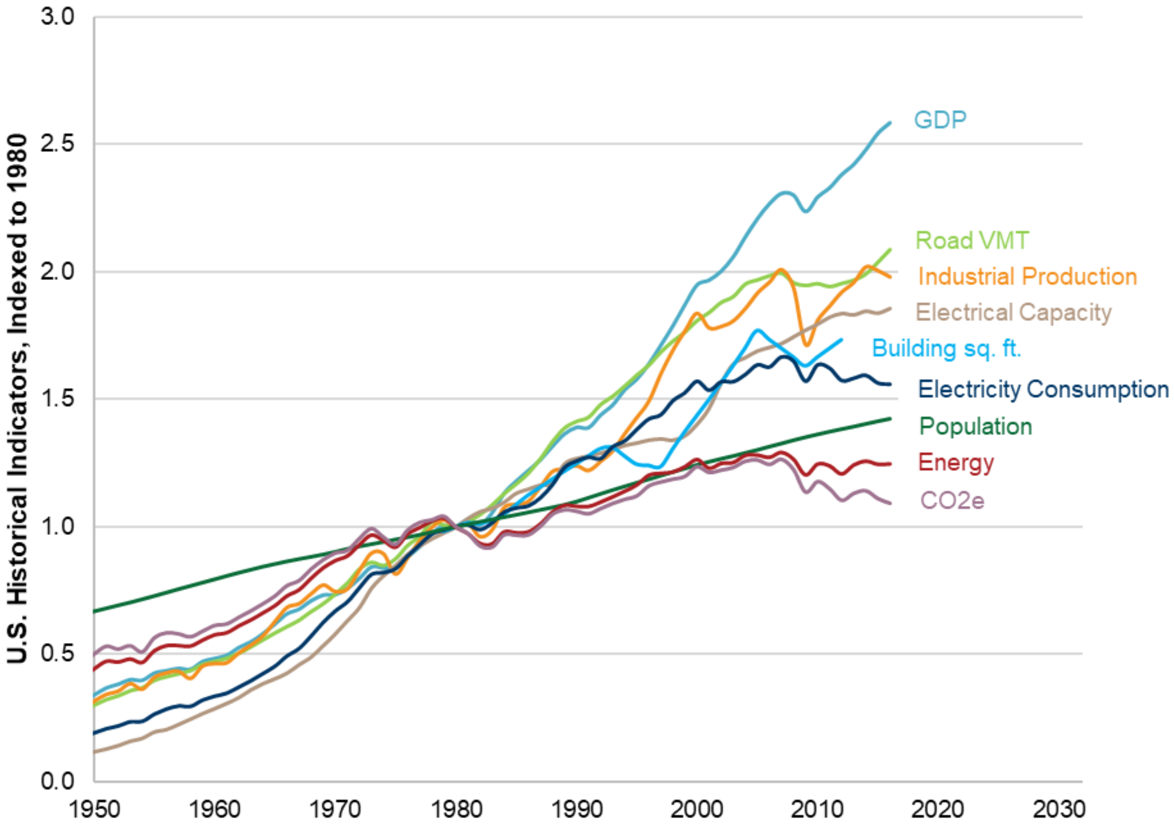

Figure 2.3. Indicators of the U.S. energy economy

Data Sources: EIA Annual Energy Review (EIA 2011), EIA Monthly Energy Review (EIA n.d.), FHWA (2015), CBECS (2012), RECS (2009), and Federal Reserve Economic Data (FRED n.d.). Building square footage is linearly interpolated between all available RECS and CBECS survey years.

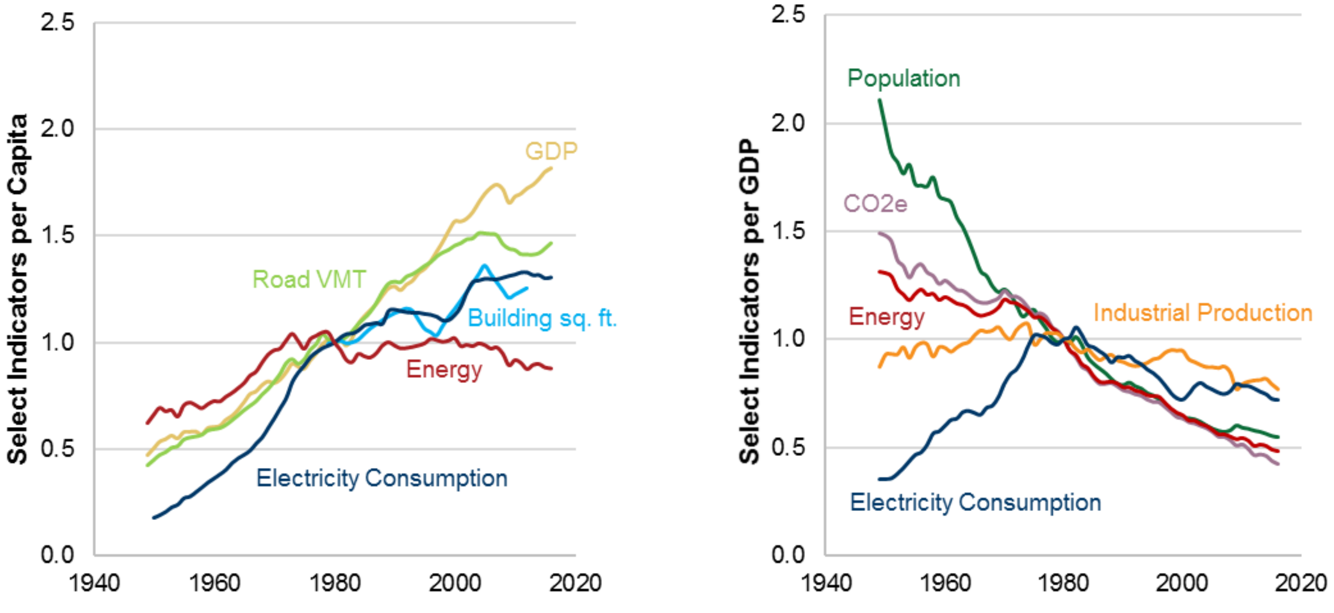

Figure 2.4. Select normalized indicators (left) per capita and (right) per dollar of GDP

Data Sources: EIA Annual Energy Review (EIA 2011), EIA Monthly Energy Review (EIA n.d.), FHWA Office of Highway Policy Information (2015), CBECS (2012), RECS (2009), Federal Reserve Economic Data (FRED n.d.). Building square footage is linearly interpolated between all available RECS and CBECS survey years. The ratios are first calculated first and indexed to 1980 values.

Trends in GDP also stand out in comparison with the other indicators. Before the late 1970s, electricity grew faster than the economy while industrial production grew at close to the same rate as the economy. Since the late 1970s, however, the rate of growth in GDP has been faster than all other indicators shown, which demonstrates that continued economic growth can continue alongside changes in electrical consumption, energy consumption, and emissions. These trends are most evidently observed in the right graph in Figure 2.4, where all traces—including population, energy and electricity consumption, and emissions—have negative slopes after 1980, indicating they decrease relative to GDP. The continued GDP growth despite decreasing energy consumption indicates an increasingly energy efficient economy (Belzer 2014; Huntington 2010). The electricity consumption trends per dollar of GDP show an interesting inflection around 1980, where the slope changes sign from positive to negative, demonstrating the reduced correlation between economic growth and electricity consumption.

Comparing relative growth rates, these data also show that the energy sector has been steadily becoming less emissions intensive and more electricity intensive, while the U.S. economy and industrial production have been steadily becoming less energy intensive. Declining emissions intensity has been starker in electricity than it has been with total energy since the 1960s, but it has been even more pronounced over the most recent decade. This decline in electricity emissions intensity provides one of the motivations for electrification, as we discussed in Section 1. The data show that electrical capacity continues to grow faster than electrical energy consumption since 2000, despite the ratio of annual peaks to average electricity demand remaining relatively constant since 1990.[19] This indicates an overall reduction in fleet-wide capacity factors as well as shifts in generation technologies discussed previously. These trends provide context for future electrification scenarios that affect system capacity, electricity consumption, and fuel mix—which are all topics of focus for future EFS reports.

In summary, the historical indicators show decreasing correlations with each other over time, suggesting growing complexities in the U.S. energy economy. Because of the increasing complexity, the impact of future energy transitions—such as widespread electrification—will likely be more difficult to assess. Despite these complexities, growing per capita GDP and service indicators (e.g., VMT, building area, and industrial production) signal that the overall quality of life to an average American has been improving with time. Over the long history, these improvements have coincided with increases in energy use and emissions, but the declining correlations between indicators during the past decade demonstrate that these increases are not inexorable. Taken together, the recent data suggest an increasingly energy- and emissions-efficient economy, especially on a per capita basis or a per GDP basis, that delivers greater services to the American people. How electrification might impact future trends in these indicators is an important research topic, and these historical data provide context for studying these impacts. The EFS presents scenarios to help explore some of these issues.

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[19] The ratio has averaged about 1.6 for the summer peak and about 1.4 for the winter peak from 1990 to 2016 (EIA 2011; EIA n.d.).

3 A History of Past Energy Transitions

In this section, we review the characteristics of energy transitions that have occurred over the past several centuries—transitions in which one energy source or technology has been replaced by another for a given sector or end use (Fouquet 2010; Grübler, Nakićenović, and Victor 1999). These transitions are driven by the development of new energy sources that are less costly than the incumbent and/or offer additional services and benefits.

Each energy sector has undergone transitions between different fuel sources at different times. Heating was originally dominated by biomass before being gradually overtaken by coal, which then quickly transitioned through oil to primarily natural gas and electricity. Mechanical power was originally supplied by food and fodder to provide human and animal labor, then incorporated wind- and hydro- and later coal-powered machines, and then switched to electricity powered by coal, oil, gas, and eventually nuclear power and renewables to reach the current electricity generation mix. Transportation was historically powered by wind (sailing) and animal fodder (horses and oxen) before being supplanted initially by coal and later by oil. Lighting began with whale oil and candles before being supplanted by gas and kerosene, which were then rapidly replaced by electricity (Fouquet 2010).

A framework for characterizing these transitions is described by Grübler, Nakićenović, and Victor (1998), where each transition progresses through several general stages: invention, innovation, niche market, pervasive diffusion, saturation, and senescence. In the invention stage, basic research results in technology breakthroughs, which leads to the applied research and development that occurs during the innovation stage. Eventually, sufficient development leads to adoption in niche markets by early adopters that are willing to pay price premiums for the improved services or social status supplied by the new technology (e.g., electric vehicles at present) or are willing to accept the risk of new technology if it is less expensive than the incumbent (e.g., LED light bulbs when considering lifetime costs). Continued development leads to the technology becoming cost-competitive and well-known, which leads to widespread diffusion and eventual market saturation. Eventually, in the senescence stage, a new technology begins to take over and the next transition occurs.

Several characteristics affect the speed at which energy transitions move through these stages. The learning rate describes the speed at which technology costs decrease as a function of experience, which can be indexed generally by cumulative output or cumulative investment. This rate of cost decrease determines when the new technology will be accessible both initially to early adopters and later to the mass market. Learning rates during commercialization are often lower than those during the initial research and development (R&D), and historically, a full transition to a new technology did not occur until the new technology was lower-cost than the incumbent (Fouquet 2010). While the learning process continues, the marketplace adoption of a technology follows an S-shaped curve over time, with an initial period of slow growth followed by an increase in adoption, followed by slow growth to saturation. Numerous factors affect the speed with which the adoption rises, including communication and/or education within markets, economies of scale, available capital, learning rates, turnover and lifetimes of existing technology, and governmental policy. Additionally, technologies that are less-expensive replacements for existing technologies (e.g., LED light bulb) diffuse faster than those that provide new and additional services (e.g., the first light bulb). Competition between the new technology and the old technology can also slow diffusion of the new technology by spurring innovation in the old technology, as may have occurred with sailboats began competing with steamships (Sick et al. 2016). This may occur if or when costs of ownership for electric vehicles approach or become lower than those of internal combustion vehicles. Additionally, the rate of development of infrastructure supporting a new technology, such as roads or electric distribution systems, can limit the rate of new technology adoption. The development of supporting infrastructure can be described by its own learning rates and diffusion curves. In the context of this report, this factor is particularly relevant for the dependence of electric vehicle adoption rates on the presence of public charging infrastructure. Moreover, technology development can support clusters of related technologies (Grübler, Nakićenović, and Victor 1999; van den Bergh et al. 2006), such as batteries, electric vehicles, and grid-scale energy storage, or hydrogen fuel cells, electrolyzers, and storage systems.

Figure 3.1 presents several historical examples of technology adoption and diffusion that loosely follow the characteristic S-curve trend described above. The earliest example (in red) is the first large-scale adoption of electrotechnologies by U.S. manufacturing firms, which began around the turn of the 20th century. Immediately prior to this transition, U.S. industry largely relied on shaft-and-belt systems driven by water power and coal-powered steam engines. By 1940, over 80% of manufacturing machine drive was provided by electric motors, an increase from less than 5% in 1899 (R. B. Du Boff 1964 in Devine 1983).[20] Household electricity access, refrigeration, and car ownership provide other older, but useful, examples of S-curve adoption, although the smoothness of the curves can be interrupted by mitigating factors such as the Great Depression and World War II. More recent examples, including air conditioning, television, and cell phone, are also displayed in Figure 3.1.

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[20] Although electric motors were more energy efficient than line shaft drives, their productivity improvements are cited as being more important factors of their adoption, highlighting that energy use or cost are not the only factors driving adoption (Devine 1983). Another significant electrotechnology adoption driven by productivity improvements occurred with the substitution of vertically integrated steel mills that use blast furnace/basic oxygen furnaces with minimills that use electric arc furnaces. This transition occurred in the second half of the 20th century, when, minimill market share of hot rolled bars, plates and shapes increased from less than 20% in 1962 to over 80% in 2002 (Collard-Wexler and De Loecker 2015). These examples highlight the importance of productivity in technology adoption in the industrial sector and foreshadow the rationale for our future scenarios as they are related to drivers of industrial electrification as presented in the Section 6.3.

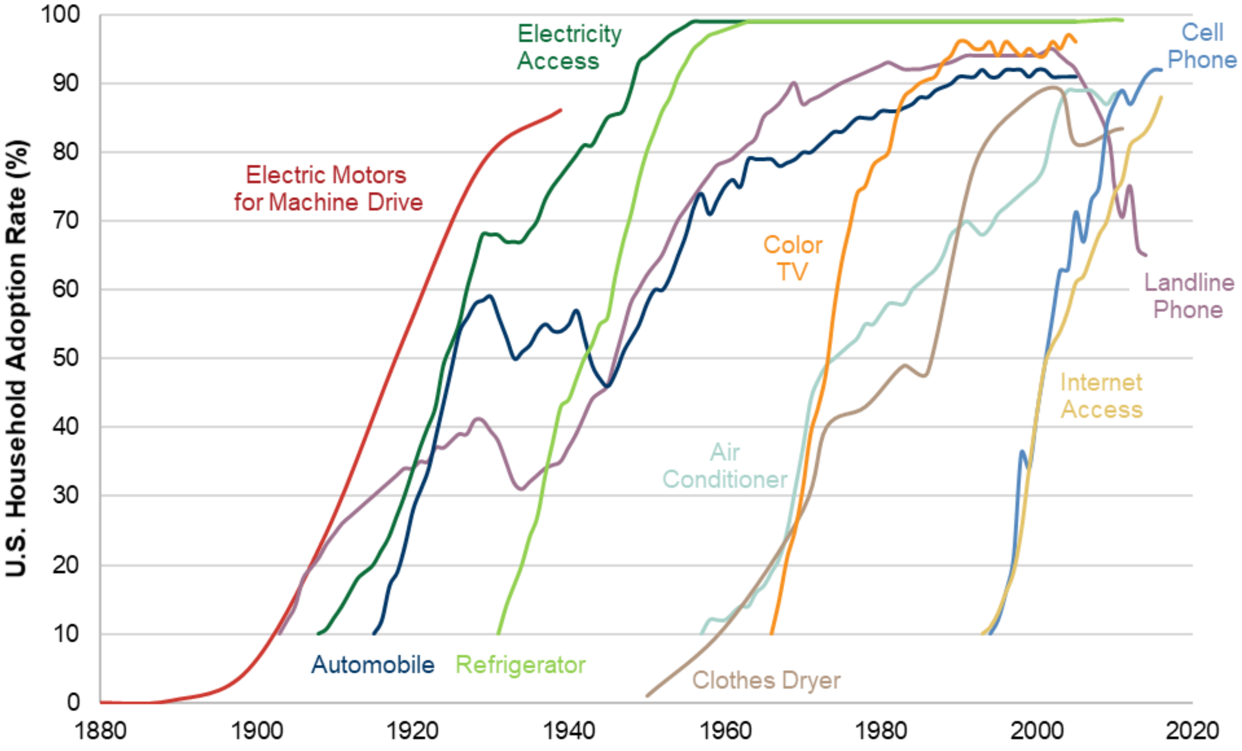

Figure 3.1. Diffusion of various technologies in U.S. households

Data Sources: Du Boff 1964 in Devine 1983 for electric motors; Ritchie and Roser 2018 for all others

Previous energy transitions have occurred over diffusion times ranging from hundreds of years (wood to coal) to 30–50 years (most post-industrial revolution transitions) (Fouquet 2010). However, given the factors that affect technology adoption, present conditions could make the speed of modern energy transitions different from those in the past (Fouquet 2010). Social media, access to information on the internet, and targeted marketing can accelerate diffusion by increasing the spread of information about a new technology both between suppliers and consumers as well as among consumers (Parkins et al. 2018). Higher standards of living and education than were present during past energy transitions may allow more disposable income to pay for price premiums in exchange for environmental or other benefits (Jager 2006; Elmustapha, Hoppe, and Bressers 2018). Governmental policies that attach the costs of externalities associated with a given fuel to its price may shift the relative economics of new technologies, leading to rapid and significant changes in adoption for technologies that are presently on the margin of cost-competitiveness. Similarly, governmental targets or mandates, such as light bulb efficiency standards, could accelerate technology adoption. New technology adoption could also be impeded by legacy policies or infrastructure, including the production and distribution systems of incumbent fuels, as well as slow stock turnover of existing technologies with long useful lifetimes, such as heating, ventilation, and air conditioning (HVAC) equipment; industrial process heating equipment; and vehicles (Fouquet 2010). Furthermore, an electrification transition, where a simple displacement of existing fuel-based technologies occurs, might not yield as-rapid or as-complete a transition as observed historically where new services, additional value, and inconvenience come with the new technologies.

The phone examples from Figure 3.1 show how the speed of transitions can differ over time. Historical data show how it took over 65 years for landline phones to grow from about 10% of U.S. households to 90% of them. In contrast, growth over the same adoption shares required only about 20 years for cell phones. This example demonstrates how changes in conditions and technologies can yield much greater transition rates today, and in the future, than they have in the past. It also shows how much more rapidly a transition can occur with a new technology providing additional benefits on top of an existing service as compared to an older technology providing a new service for the first time. The replacement of landline phones by cell phones occurring since around the year 2000 is the beginning of the senescence phase of the transition, which, in this case, appears to also proceed at a rapid pace. Of course, specific conditions could yield different outcomes for other technologies. Figure 3.1 highlights the historical diversity of possibilities, but also the general consistency of the S-curve shape of adoption and diffusion patterns.

Forecasting future energy consumption is notoriously unreliable, and there is a long history of unpredictability and volatility in energy indicators, particularly in the most recent decade (Sherwin, Henrion, and Azevedo 2018; Craig, Gadgil, and Koomey 2002). While the EFS does not attempt to forecast the future, past energy transitions, such as the brief examples mentioned here, can provide useful guidance and frameworks for modeling scenarios of how future transitions might unfold even though factors and conditions that influence potential transitions remain unpredictable (Craig, Gadgil, and Koomey 2002). In addition, multiple potential barriers to technology adoption (Parente and Prescott 1994) exist that are specific to each technology or sector, requiring high fidelity in any modeling framework.

In this report and the broader EFS, we explore future scenarios of the U.S. energy system undergoing an electrification transition to assess the potential impacts of this transition. Our scenario design methodology uses S-shaped diffusion curves that are informed qualitatively by the experience from past energy transitions. It is important to note that we do not rely on consumer choice models across all technologies due to the substantial modeling challenges to execute this approach comprehensively for all sectors and with high resolution (Sections 4–5 detail our approach). Such modeling would help reveal the drivers of and barriers to electrification, and it would inform the policies or actions needed to overcome them (e.g., Deason et al. 2018). We identify this as a future research need.

4 Scenario Design

For this analysis, we develop multiple electricity consumption scenarios with variations along two primary dimensions: (1) end-use electric technology adoption and (2) electric technology cost and performance. Along the adoption dimension, we model three levels of electric technology adoption and refer to these levels as *Reference*, *Medium*, and *High* electric technology adoption levels. For each of these adoption trajectories, we model three technology cost and performance projections, which we refer to as *Slow*, *Moderate*, and *Rapid* technology advancement projections (Jadun et al. 2017). Because different levels of technology advancement can result in various equipment energy efficiencies as well as cost reductions, an assessment of overall electricity consumption must consider both the amount of adoption as well as the technology evolution. In all, we develop nine scenarios—three electrification levels times three technology advancements (Table 4.1).

Table 4.1. Scenario Framework

		Technology Advancement (Jadun et al. 2017)		
		Slow	**Moderate**	**Rapid**
Technology Adoption (this 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

We model variations in both dimensions—technology advancement and adoption—to capture the sizeable uncertainties in both. Moreover, our methodology relies on an accounting framework (see Section 5) rather than dynamic consumer choice modeling. Hence, our approach and the scenarios represent projections to study the impacts of electrification rather than predictive forecasts. In this section, we present the numerical inputs that define these scenarios. We also qualitatively discuss the rationale behind their design.

4.1 End-Use Electric Technology Adoption

Along the adoption dimension, we develop three adoption trajectories: Reference, Medium, and High.[21] We first describe qualitatively the assumed characteristics of each of these scenarios and then follow with the quantitative assumptions that define the scenarios.

The Reference electrification adoption scenario represents a business-as-usual outlook where only incremental changes with respect to electrification occur. In particular, the Reference scenario includes policies that existed in 2017 only. It also excludes any dramatic technological, societal, or behavioral shifts as they relate to the adoption of end-use equipment. It reflects a future in which the rate of adoption of electric technologies roughly follows current trends. In other words, an electrification transition, in the sense described in Section 3, remains in the earliest stages even by 2050. The Reference scenario serves as a baseline of comparison for the Medium and High electrification scenarios; unless otherwise noted, all incremental values are presented with respect to the Reference scenario outcomes.

The Medium and High electrification scenarios represent futures with levels of electrification that are greater than in the Reference and are beyond current adoption rates. The Medium and High scenarios are both designed to enable an assessment of the impacts of widespread electrification on electricity consumption, as well as the consequences of the resulting changes in consumption. We do not intend to suggest that greater electrification is likely or desirable; rather, conclusions about whether this outcome is beneficial (and to whom) will be informed to some extent by the broader EFS analysis. Together, the Reference, Medium, and High adoption scenarios span a considerable range of electrification futures and establish the basis for understanding widespread electrification, which is the primary focus of the EFS.

The Medium scenario is intended to reflect an electrification future that is plausible but not transformational. It includes accelerated adoption of electric technologies serving end uses in all sectors; however, electric technologies are not ubiquitous in this scenario, as we assume technical, economic, and consumer preference obstacles remain for certain end users. Even for services where increased electrification is assumed to occur, adoption of end-use technologies often remains in the diffusion stage or saturates at somewhat modest levels by 2050 in the Medium scenario. For other services, electrification is assumed to still be at the early stages with uptake occurring only in limited markets and by early adopters.

The High scenario assumes a more favorable set of conditions for electrification—including a combination of technology breakthroughs, policy support, and underlying societal and behavioral shifts that yield an electrification transition. As a result, the High scenario reflects an increase in the degree of electrification in the areas considered in the Medium scenario as well as additional subsectors where electrification takes hold. In the S-curve characterization of technology diffusion (see Section 3), the electric technologies generally experience earlier saturation in

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[21] These three terms—Reference, Medium, and High—are all used to describe the amount of technology adoption and the degree of electrification. The amount of electricity consumption (megawatt-hours) is determined by the technology assumptions (efficiencies) as well. However, we note that the share of services provided by electric technologies is specified by the adoption amount only (in combination with equipment utilization and lifetime assumptions) and independent of equipment efficiency.

the High Scenario. This scenario does not reflect a full technical potential for electrification, but it does represent an aggressive electrification future where many obstacles to electrification are overcome.[22]

The Reference, Medium, and High scenarios are defined principally by expert judgment by the authors and based on a combination of modeling, analysis of current trends, projections and results from previous studies (EIA 2017c). Technology adoption is impacted by a wide range of factors including economic trade-offs, consumer preference, and policies. Text Box 4.1 categorizes some of the factors that might ultimately affect individuals' or corporations' decisions to procure new technologies. The cost of the new technology relative to existing ones, which is one of the primary factors highlighted in Text Box 4.1, may motivate adoption and switching especially when cost differentials are material to the potential adopter. But the potential for stranded costs for suppliers of goods and services for existing technologies can introduce tensions. Other factors, which can impact the relative economics or are non-economic in nature, can also often play a sizeable role, as Text Box 4.1 summarizes. In addition, and as discussed in Section 3, the speed at which new technology adoption and diffusion occurs can also be impacted by other trends, such as social connectivity and communications. These factors were considered in the study team's determination of the expert judgment-based adoption levels in the electrification scenarios. For example, we assume industrial electrotechnologies with limited or no direct benefits to industrial productivity (e.g., electric boilers) are not adopted under the Medium scenario. Table 4.2 highlights some of the key distinguishing aspects between the Medium and High electrification scenarios. Details of how the quantitative scenario definitions were generated are summarized below and described in detail in Appendices B–D.

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[22] Appendix F presents results from two additional bounding scenarios modeled, including a scenario that reflects a technical potential of electrification in a narrow sense as described in the appendix.

Text Box 4.1. Factors that Impact Technology Adoption

A myriad of factors can impact whether new electric technologies are adopted. In this text box, we present five categories of factors that we believe are most relevant to adoption decision-making for end-use electric technologies. The factors overlap, have varying impacts, and can be synergistic or competitive. Nonetheless, these factors were *qualitatively* used in our scenario design.

- **Costs** reflect the direct economic competition—affected by technology cost and efficiency, fuel costs, equipment lifetimes, and financing terms—between electric and alternative end-use technologies that can provide similar end-use services. Actual and perceived costs can be impacted by the other factors described below.
- **Supporting infrastructure** refers to the cost or availability of supporting equipment or process change that might be needed to enable electrification.
- **Ownership and availability** reflect the relationship between the equipment owner and service-receiver as well as the accessibility of electric technologies.
- **Health and sustainability** includes environmental policies and regulations as well as the degree of preference for equipment with lower environmental footprints.
- **Other factors** include additional or improved services as well as value streams that could be enabled by electrification, such as providing electricity grid services, increasing productivity, and improving product or service quality. This category also includes consumer preference factors, such as design and performance.

A future with large and rapid adoption rates of electric technologies, such as that represented in our High scenario, would likely require many or all these factors to evolve in manners that are supportive of electrification or electric technologies. Below, we list specific examples of *favorable conditions that might incent electric technology adoption* for each sector.

- **Transportation:** Continued advancements in battery technologies help lower electric vehicle costs while smart vehicle charging complements friendly electricity rate structures and low electricity rates. A large network of public, workplace, and/or utility-owned charging stations reduces range anxiety while fast and efficient charging technologies (e.g., induction-based, DC-based, and catenary technologies) reduce inconveniences, even for longer trips or larger vehicles. Optimal smart routing and urban planning further reduce infrastructure needs and costs. With favorable economics for PEVs, fleet managers—for passenger and freight services—can implement a rapid turnover. Expansion of car-sharing services, perhaps enabled by automation, would enhance this fleet impact. Vehicle manufacturers follow these trends and develop and market a diverse set of model options serving nearly all consumer preferences for design, convenience, and performance. A combination of local, state, and federal policies—such as air pollution standards, efficiency standards, and gasoline taxes—lead to economic incentives and/or mandates for PEVs. Furthermore, drivers recognize or perceive the possible noise, acceleration, and convenience benefits of electric vehicles leading to greater adoption.

- **Buildings:** Electric heating, cooling, and cooking technologies improve and become economically attractive even under challenging conditions (e.g., heat pump performance in cold climates). Improvements in the compatibility of electric technologies with existing buildings facilitate their adoption through retrofits or remodels. Landlord-tenant problems associated with adoption of electrification home improvements in rental spaces and multi-family dwellings are overcome through the help of energy service companies, incentives, or public policy. The full supply chain for buildings electric technologies—including appliance manufacturers, retailers, and contractors—evolve to increase the availability of and facilitate the installation of electric technologies. Local building codes and policy aims, such as net zero energy or emissions targets and indoor air quality, favor electric technologies more than combustion-based ones. Widespread implementation of demand response programs creates increased incentives for controllable electric loads, including those associated with space and water heating. Finally, buildings electric technologies are found to provide greater non-energy benefits, such as comfort, safety, and controllability for cooking, heating, and other services.

- **Industry:** Stable low-cost electricity combined with significant electrotechnology improvements favor industrial electrification. Low-cost financing could further enhance adoption of electrotechnologies to replace existing furnaces and other capital-intensive industrial equipment. The successful adoption of and familiarity with electric technologies by leading firms would encourage technology diffusion to other companies and industrial uses. Electrotechnologies are also found to provide recognized non-energy benefits, such as improved production rates and product quality through increased precision and control for manufacturers. Industrial electrification is spurred by environmental policies and corporate sustainability goals, and it is used to meet standards set by domestic and export markets.

The above examples provide conditions that might be conducive to the adoption of electric technologies; however, many situations can make electrification challenging. Barriers to electrification can be economic, as many electric technologies have higher upfront costs than incumbent technologies today. Lack of available capital would discourage the necessarily investments irrespective of relative life-cycle costs. Uncertain fuel and electricity prices (and rate structures) also impact economic competitiveness. Technology development and breakthroughs might also be needed for widespread electrification for certain end uses (e.g., high-density batteries, fast-chargers, cold-climate heat pumps, and high-temperature industrial electrotechnologies). Resistance from incumbent technologies as well as improvements in existing technologies could increase the economic challenge to new technologies. Beyond economic and technical factors, social and behavioral factors may also act as barriers to electrification. These factors include consumer, manufacturer, supply chain unfamiliarity, and reticence with new technologies. Examples include “range anxiety” for electric vehicles and preference for natural gas cooking by home and commercial chefs. Other examples include perceived risks with new technologies from manufacturers and experience or training with equipment installers.

Ultimately, there are uncertainties across many dimensions—and region- and system-specific considerations—that would impact adoption. We have listed some qualitative factors here, but we note that much research is needed for quantitative analysis. Although consumer choice models are not used comprehensively in the EFS scenarios, well-designed adoption models would consider these factors. Ultimately, understanding drivers would be helpful to inform all decision makers.

Table 4.2. Summary of Differences between Electrification Scenarios

	Transportation	Buildings	Industry
Reference Electrification	PEV sales shares from AEO2017 Reference case; PEV adoption is largely restricted to LDVs	Stock shares from AEO2017 Reference	No incremental electrification
Medium Electrification	Growing PEV adoption for LDVs; MDVs, HDVs, and passenger bus electrification is primarily limited to short distance uses only.	Growing electrification for cooking, clothes drying, and space and water heating; ASHP adoption primarily in milder climates; limited cold-climate ASHP adoption	Growing adoption of electrotechnologies but limited to technologies that offer potential productivity benefits
High Electrification	High PEV adoption in light-duty vehicles and passenger buses; plug-in electric MDV and HDV expands to both short and long distance uses.	High adoption of all electric building technologies considered, including substantial adoption of ASHPs in cold climates	Growing adoption of technologies without productivity benefits in numerous subsectors, and High adoption for technologies with productivity benefits; accelerated equipment replacement.

AEO = Annual Energy Outlook
ASHP = air source heat pump
LDV = light-duty vehicle
MDV = medium-duty vehicle
HDV = heavy-duty vehicle
PEV= plug-in electric vehicle

Mechanically, the electrification scenarios differ by the amount of new sales of the electric technologies considered (Table 4.3) using the EnergyPATHWAYS accounting framework (Section 5).[23] In this way, the impacts of electrification are isolated from other effects. In the following, we present the annual sales shares through 2050 for each electric technology modeled in each scenario. Note that we took a different approach for industry due to the difficulty of obtaining publicly available equipment sales data. Instead of annual sales share, industrial electrification is represented as the fraction of new production capacity that is electrified in each year.

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[23] Total service demand is held constant in all scenarios.

Table 4.3. Substitute Electric Technologies Modeled

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 transit buses**	**Air source heat pumps** Ground-source heat pumps **Heat pump water heaters** Electric stovetops and ranges Electric dryers	**Air source heat pumps** (for space conditioning) Electric machine drives Industrial heat pumps, induction furnaces, infrared heating, and resistance heating for process heat, including drying Electric boilers Ultraviolet heating

Technologies in **bold** are modeled with variations in cost and performance based on the Slow, Moderate, and Rapid technology advancement assumptions from Jadun et al. (2017). Greater adoption of all electric technologies is modeled in either the Medium or the High scenario, relative to the Reference scenario.

For most electric technologies, sales shares in both the Medium and High scenarios follow S-shaped curves by design, qualitatively matching trends observed historically for many new technologies.[24] In fact, for many technologies, the S-shape curves in our implementation follow the same logistic functional form[25] for the Medium and High scenarios, except a slower adoption rate and lower saturation level occurs for the Medium scenario. For buildings and industry, adoption heuristics used to inform the parameters for the S-curves are presented in Appendices C and D, respectively. We note the dearth of literature on adoption across different end uses and industries in the industrial sector in particular. Absent available data or modeling, our heuristics for industry limit the opportunities to electrify end uses with technologies (e.g., electric boilers) that do not have industrial productivity benefits (e.g., increased production rates and improved product quality), even under a high electrification scenario. We assume electrotechnologies with limited or no productivity benefits are not adopted under the Medium scenario. Our choice to view industrial electrification through the lens of productivity benefits may result in conservative adoption assumptions for many electrotechnologies. Additionally, we note that energy-intensive industries—such as the steel, cement, chemicals, and pulp and paper industries— in general face significant barriers to innovation that result from their industry and market structures, high capital intensity, and long investment cycles, and such industries focus on incremental technology improvements, among other factors (Wesseling et al. 2017). Table 4.2 summarizes some of the key differences between the Medium and High electrification scenarios.

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[24] Exceptions are obvious from Figures 4.1–4.3 and include light-duty vehicles where we use projections from ADOPT in the Medium scenario.

[25] The logistic function is defined as $f(t) = A + ((K - A) / (1 + \exp(-B * (t - M))))$ where t is the year, f(t) is the sales share during year t, A is the starting penetration, K is the final penetration, M is the inflection year where the rate of change is greatest, and B is a constant set to 10 / (end year – start year).

Technology Sales Shares in the Electrification Scenarios

Under the Reference scenario, adoption of electric technologies closely follows that from the AEO2017 Reference case developed by EIA (2017c),[26] which relies on economic modeling using NEMS and input assumptions therein. Figures 4.1–4.3 (following pages) show the sales shares of modeled electric technologies for select end uses in the three adoption scenarios. We note that available market is based on the service demand growth and existing equipment lifetime assumptions applied in EnergyPATHWAYS (Section 5); we do not assume earlier-than-expected or premature retirements in any of the scenarios.[27] Unlike is done with the transportation and buildings sectors, we model electric technology adoption in industry as the fraction of annual new capacity (measured in dollar value of shipments).

In the Reference scenario, PEVs—including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)—comprise 22% of 2050 light-duty car sales, 2.4% of light-duty trucks, and <1% of medium- and heavy-duty trucks or buses. Heat pump sales make up 21% and 13% for 2050 residential and commercial space heating, respectively, in this scenario.[28] Even smaller sales shares are assumed for heat pump water heating (2% in 2050 for both residential and commercial) as shown in Figure 4.2. For the industrial sector, we assume no additional electrification beyond the AEO2017 Reference case. The Reference case projects the electricity share of industry site energy use to remain essentially flat through 2050, although this does vary by industry.[29] The largest changes are in the pulp and paper and iron and steel industries; AEO2017 (EIA 2017c) projects purchased electricity's share of site energy will decrease at a CAGR of 1.3% in the pulp and paper industry and increase at a CAGR of 1.3% in the iron and steel industry. Additionally, electric boilers are not used in any industry.[30] In summary, 2050 sales shares of electric technologies under the Reference scenario are not significantly higher than shares today for most end-use sectors.

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[26] The AEO2017 Reference case includes the Clean Power Plan, the Corporate Average Fuel Economy (CAFÉ) standards, and other policies and regulations as of 2017.

[27] However, as noted below, we assume more-rapid turnover for industrial equipment in the High scenario than the others, except for space heating; industrial equipment lifetimes are assumed to be 50% shorter in the High scenario.

[28] In the Reference scenario in 2050, electric resistance heaters make up 4%–5% of sales for both residential space heating and commercial electric boilers comprise another 3%.

[29] This is based on assumptions made in the NEMS Macroeconomic Activity Module (EIA 2018).

[30] AEO electric boiler assumptions contrast with data reported by EIA MECS. The latest MECS data indicate that electricity provided as much 4% of conventional boiler use in 2014 (MECS 2017).

Figures 4.1–4.3 also show the sales shares for electric technologies for select end uses under the Medium and High scenarios. For the Medium scenario, we assume PEVs comprise up to 69% of light car and truck sales shares by 2050 (Figure 4.1),[31] which reflects the fact that the NREL Automotive Deployment Options Projection Tool (ADOPT) indicates that significant electrification is possible for light-duty vehicles (LDVs), even after accounting for the modeled economic and non-economic factors determining consumer adoption choices. The accelerated growth in light-duty PEV adoption through 2022 and the non-monotonic behavior in PEV sales shares in the 2020s in the Medium scenario are driven by the representation of Corporate Average Fuel Economy (CAFE) standards and other assumptions in ADOPT (see Appendix B). We assume that by 2050, 29% of MDVs have electric drivetrains, while electric vehicles comprise 10% of all heavy-duty truck sales and 50% of all transit bus sales in the Medium scenario. The lower sales share for electric HDVs reflect potentially larger (and more-costly) battery requirements and associated considerations for larger and heavier vehicles. Additionally, because of these potential challenges, electric medium- and heavy-duty trucks are largely restricted to short distance uses such as vocational vehicles and short-haul delivery. These distance factors are considered in our expert judgment-based sales shares for MDVs, HDVs, and electric buses (Appendix B).

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[31] Long-term (2040 or 2050) PEV sales shares in the Medium scenario fall toward the high end of the range of estimates from recent studies, including Stephens (2017), BNEF (2017), and OPEC (2017). However, the Medium scenario includes a more rapid PEV growth rate in the near term than these other estimates. In contrast, the Reference scenario, which is aligned with the AEO2017 Reference case, falls below many of these estimates of 2050 PEV sales.

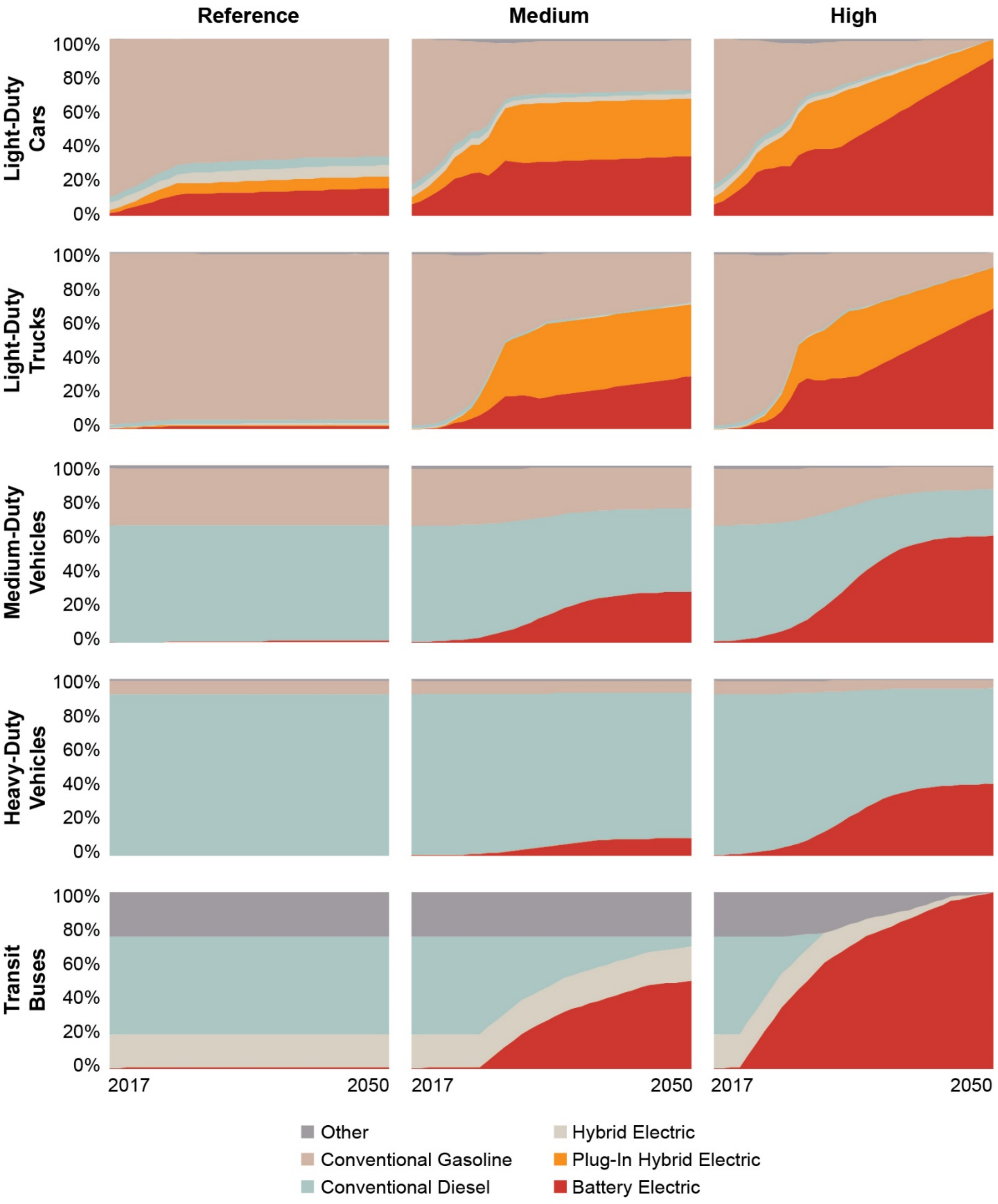

Figure 4.1. Transportation technology sales shares by electrification scenario

Other vehicle types include those relying on natural gas and hydrogen fuels.

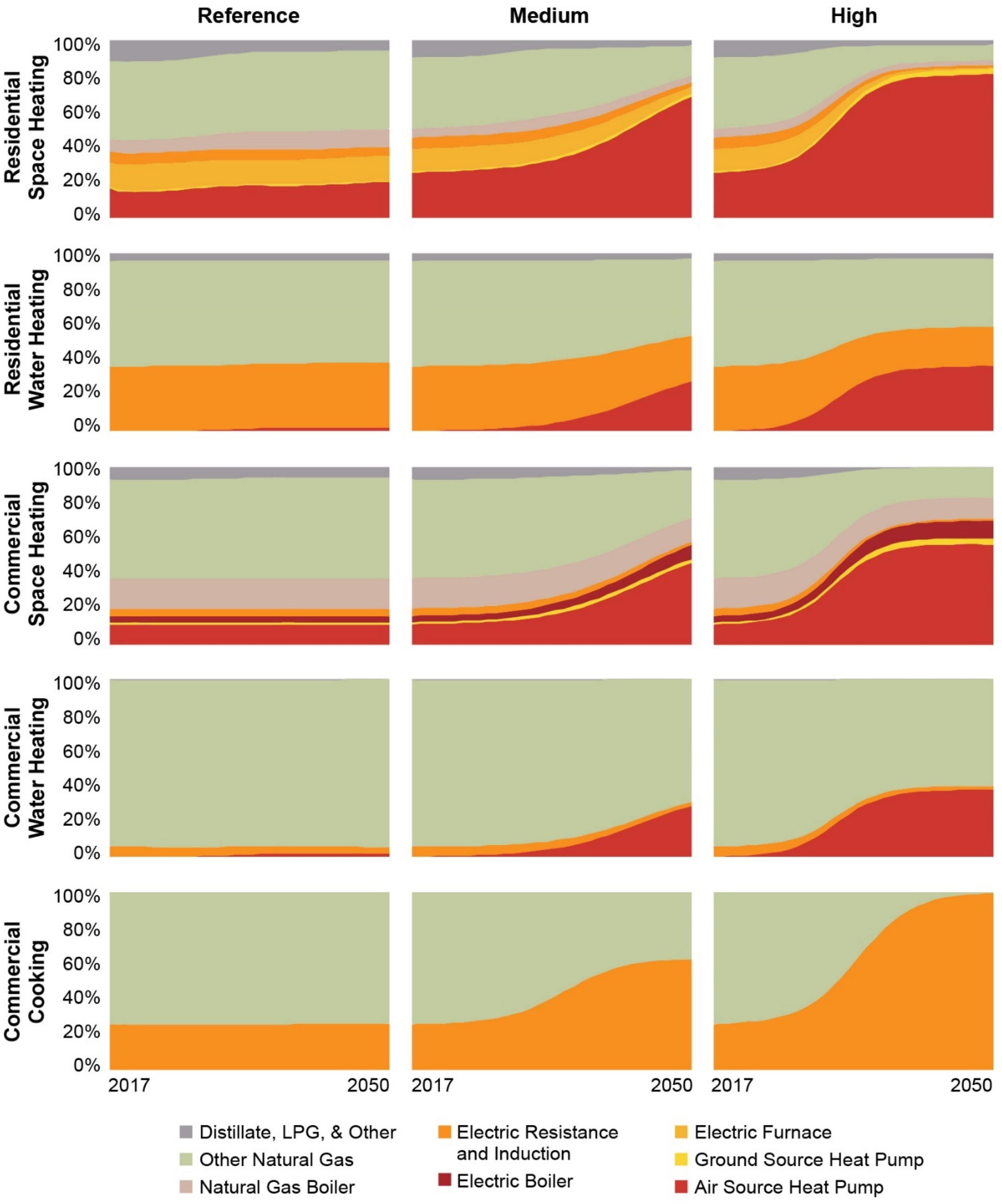

Figure 4.2. Buildings technology sales shares by electrification scenario

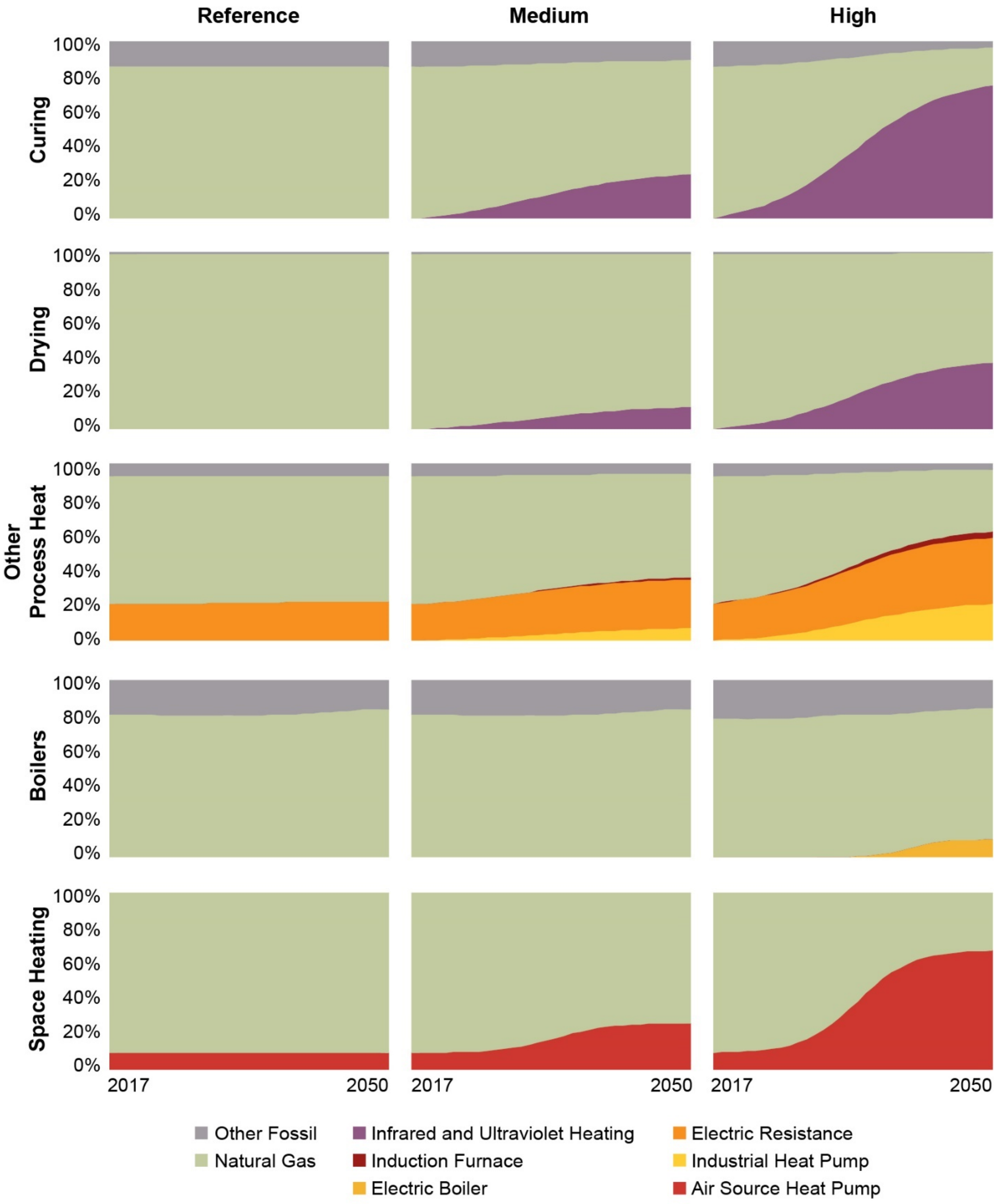

Figure 4.3. Industrial technology sales shares by electrification scenario

For buildings, we assume the sales share of air source heat pumps for space heating reach about 68% and 46% for the residential and commercial sectors, respectively, by 2050 (Figure 4.2).[32] This increase is predominantly driven by an assumption that heat pumps become the dominant technology across all hot and moderate climate regions, while sales in cold climates continue to be dominated by natural gas technologies. Sales of heat pump water heaters, electric cooktops, and clothes dryers are also assumed to increase substantially from the Reference scenario. Appendix C provides details on the expert judgment-based shares for the buildings sectors. For industrial electrotechnologies with moderate and large productivity benefits, we assume they constitute 10% and 25% of new capacity additions by 2050, respectively. For example, process heating electrotechnologies constitute 25% of new capacity in the glass, and plastic and rubber products industries. Appendix D presents the adoption heuristics used in industry.

The High scenario assumes a more favorable set of conditions for electrification and therefore includes more-complete electrification across all end-uses considered such as LDVs as well as significant adoption of electric HDVs (41% by 2050) even for long-haul applications. For building space heating, we assume geographically widespread adoption of heat pumps in the High electrification scenario, even in colder climates—resulting in approximately a 50% sales share in cold climates and a small (10%), but significant, sales share in very cold climates.[33] Adoption of industrial electrotechnologies is also significantly higher in the High scenario than either the Medium or Reference scenarios. However, this is limited to industrial electrotechnologies we assume have large productivity benefits. Quantitatively, for the High scenario, we assume industrial electrotechnologies constitute 25% of new capacity additions by 2050 for those technologies without sizeable industrial productivity benefits and 75% for other technologies with large productivity benefits. For example, under the High scenario, we assume electric machine drives constitute 25% of new capacity for agriculture non-electric machine drive, which have little productivity benefit, and induction furnaces constitute 75% of new capacity for transport equipment process heating, which offer productivity benefits. Additionally, we assume the lifetimes of all industrial equipment, except for HVAC equipment for industrial buildings, are reduced by half in the High electrification compared with the Medium and Reference scenarios.

4.2 End-Use Electric Technology Cost and Performance

The end-use electric technologies that experience greater adoption in the EFS scenarios are listed in Table 4.3.[34] For a subset of these technologies—used primarily in the transportation and buildings sectors and shown in bold in the table—that are likely to have the most impact on electricity consumption and system costs, we include variations in the degree of future technology advancement. Specifically, for these technologies we rely on three technology cost and performance projections—*Slow*, *Moderate*, and *Rapid*—presented in a separate report in the

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[32] Greater sales shares of ground source heat pumps are also found in the Medium and High scenarios, relative to the Reference. In 2050, ground source heat pumps in the commercial space heating total 1%, 2%, and 3%, respectively in the Reference, Medium, and High scenarios. Similar but generally smaller shares are assumed in the residential sector.

[33] The lower sales share in very cold climates assumes that technological and economic hurdles for cold climate heat pumps operating in cold climates are overcome, but that their lower performance at very low (subzero) temperatures continues to challenge consumer adoption.

[34] Our analysis includes existing technologies only.

EFS series (Jadun et al. 2017). The projections cover a range of future advancements in terms of capital costs, maintenance costs, and efficiencies.[35] For the buildings electric technologies that are not highlighted and not assessed in Jadun et al. (2017), we assume cost and performance from the AEO (2017) Reference scenario. Our analysis also does not include sensitivities of non-electric technologies. The technology cost and performance for these technologies are largely from the AEO2017 Reference case (EIA 2017c). We do not model cost and performance of industrial technologies due to lack of data.

The Slow advancement case is intended to reflect current technology trends without major advances, while the Rapid advancement case is intended to reflect a future where greater research and development (R&D) investments and deployment of electric technologies lead to significant cost reductions and performance improvements (relative to today and to the Slow case) by 2050. The Moderate case is intermediate between the Slow and Rapid cases. We model all three technology cases for each of the adoption scenarios (Table 4.1) due to the wide range of possibilities in future technology innovation and adoption. For example, we assume electric vehicle battery costs decrease to $80 per kilowatt-hour (kWh) by 2033 in the Rapid case, but battery costs do not drop below $175/kWh by 2050 in the Slow projection.[36] Similarly, in the Rapid case, we assume efficiency improvements of 116% from 2015 to 2050 for residential air source heat pumps but only a 79% improvement in the Moderate case and 24% improvement in the Slow case over the same period.[37]

Jadun et al. (2017) describe the qualitative and quantitative differences between the three technology trajectories. It also details the methodological approach used to construct these cases for the buildings and transportation technologies, including a combination of literature-based values and expert opinion. Because of limited data and analysis, the report does not include cost and performance projections for technologies in the industrial sector. But, Jadun et al. (2017) do summarize the data and reports that do exist, and they highlight numerous research gaps. As a result of the data sparsity in the industrial sector, we do not run technology advancement sensitivities for it and we note this as a key uncertainty in our results.

For this report, the range of technology advancements mainly affects electricity consumption estimates of the electrification scenarios (Section 7). Future technology innovation would also impact scenario costs, particularly incremental costs to the energy system and consumers; these costs will be presented in future EFS reports.

4.3 Caveats and Limitations

The scenario construct for the demand-side electrification scenarios has certain key limitations. First, we do not apply detailed consumer choice modeling for all end-use technologies in the adoption scenarios; the expert judgment-based adoption projections considered only economic and non-economic factors qualitatively. In this section, we highlight the various potential drivers of electrification; however, our analysis does not quantify the relative impacts of the different

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[35] Jadun et al. (2017) notes that the "technology data in [the] 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."

[36] Battery cost projections are based on Howell (n.d.), Moawad et al. (2016), and conversations with DOE Vehicle Technologies Office (see Jadun et al. 2017).

[37] Different improvement levels are assumed for cold-climate heat pumps (see Jadun et al. 2017).

drivers. Therefore, the scenarios should not be interpreted as predictions or forecasts of technology uptake or advancement.

Well-designed consumer choice models consider many of the factors described in Text Box 4.1, including the heterogeneity of the decision makers (Al-Alawi and Bradley 2013; Swait and Adamowicz 2001; Stephens et al. 2017; Tardiff 1980). In other words, they compare the economic case for different technology options from the perspective of different potential owners, but they also take into account non-economic factors, such as risk, convenience, appearance, and comfort. These models have been used to predict adoption, inform policy interventions, and assess drivers for future technology uptake. However, we are unaware of a comprehensive model or set of models with detailed consideration of economic and non-economic factors for all end-use technologies in the entire United States. Such models do exist for certain technologies and subsectors, but customer adoption models for all electric technologies examined in the EFS are lacking. The limited extent to which these models are employed for the EFS include ADOPT, which is used to inform the evolution of the LDV market in the Medium electrification scenario. Details from this analysis are presented in Appendix B.[38] We also leverage results from the EIA National Energy Modeling System model, which includes consumer choice modeling of heat pump adoption in the buildings sectors and a select number of other end-use technologies and subsectors (EIA 2017a; EIA 2017b; EIA 2017c; EIA 2018).[39] However, we are unaware of any detailed consumer choice models for the industrial sector, and adoption modeling for non-light-duty transportation technologies is at an early stage of development (Miller, Wang, and Fulton 2017). The lack of consumer choice modeling for all end uses is admittedly a shortcoming in our analysis, and we note that this is an area of research need.

Second, we use the same explicit or implicit assumptions for service demand, population growth, economic growth, and other similar factors in all scenarios.[40] In reality, energy transitions such as demand-side electrification scenarios represented in our analysis could influence dynamics that are not captured in our modeling framework. For example, adoption of new more-efficient equipment could lead to greater use of that equipment. These “rebound” effects are not captured in our analysis. Other dynamic feedback (e.g., climate-related feedback, demographic shifts, or trade) involving adoption and service demand are similarly not captured in our analysis. New technologies could also dramatically affect service demand and energy use in ways that are difficult to accurately predict. Significant uncertainties exist in these issues and future work is needed to better understand these complex interactions.

Third, our technology advancement sensitivities represent perfectly correlated variations in future cost and performance of all end-use electric technologies (e.g., the rapid advancement scenarios assume both PEVs and heat pumps are more cost-competitive than the slow advancement scenarios), whereas, in reality, the rate of technology advancement might be different between end-use technologies within or across sectors. However, the technology advancement projections (and adoption scenarios) were designed qualitatively, using expert

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[38] We also plan to use a detailed customer adoption model for distributed photovoltaics; however, that analysis will be presented in a future EFS report.

[39] The DOE Scout model (Harris n.d.) also includes a reduced-form representation of end-use device adoption decision-making, but largely mimics the approach used in the NEMS.

[40] For these factors, we rely on assumptions and outcomes from the AEO2017 Reference case.

judgment, to have similar levels of optimism across technologies, end uses, and sectors by considering relative economics and current trends. This approach is admittedly imperfect. Although in some cases, correlations in technology advancement between electric technologies do exist (e.g., battery improvements would benefit multiple electric end-use devices), the correlations do not exist for all technologies. Overall, our technology advancement and electrification scenarios are intended to capture a range of outcomes but are not intended to identify the most likely one.

Fourth, our analysis focuses on the *demand*-side adoption scenarios, but adoption can also be impacted by changes to the supply side, particularly electricity system evolution and possible constraints. For example, increased electrification will require additional bulk power system infrastructure (generation and transmission) as well as distribution-system equipment. These requirements could increase electricity rates, thereby disincentivizing electrification, or they could physically limit electrification growth rates due to household system or distribution system (e.g., voltage or other electrical) constraints. Future research is needed to interactively assess supply- and demand-side changes.

Finally, our scenarios do not explicitly account for technology disruption or significant unexpected or unpredictable events. Breakthroughs in electric technologies could yield much more-rapid adoption than we envisioned in any of the scenarios. Our analysis focuses on existing known technologies only.[41] Conversely, technology success in non-electric technologies could slow the adoption or innovation in electric technologies. For example, widespread automation of vehicles could dramatically impact VMT or vehicle ownership (Stephens et al. 2016). In another example, widespread growth in 3-D printing could spur electricity use in manufacturing. Beyond the technologies, dramatic changes in policies, financing, and behavior could also alter the landscape for electrification. Disruptive technologies and factors could, of course, influence all sectors.

Understanding these limitations in our demand-side scenarios is needed to appropriately interpret the findings from our analysis. The EFS scenarios are designed to estimate the impacts of various degrees of electrification under plausible conditions. Despite the limitations of our scenarios, the scenarios span a wide range of technology cost and adoption conditions to capture the significant uncertainties in these factors. The demand-side electrification levels also provide a basis to evaluate the supply-side evolution and impacts, which will be the foci of future EFS reports.

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[41] Furthermore, we omit certain existing key technologies (e.g., plug-in hybrid electric vehicles for medium- and heavy-duty transportation, ground-source or geothermal heat pumps) that could play a growing role.

5 Methodology

EnergyPATHWAYS (EP)—a bottom-up energy sector tool with stock-level accounting for all consuming, producing, delivering, and converting energy infrastructure—provides the analytic backbone for the electric technology adoption and power consumption scenarios presented in this report. The model was initially built for use in California to investigate energy system transformations, and to this end, the model leaves most energy system investment decisions to the user (Williams et al. 2011). Thus, it is appropriate to think of EP as a complex accounting system or simulation model that tracks and determines the implications of detailed user decisions. In this section, we provide a brief description of the model, new model features included for the EFS, and the key assumptions used for the present analysis. The model code itself has been made open-source and more extensive documentation can be found online.[42] Publications using the current EP model or its progenitors also describe additional facets of the methodology (Gordon 2014; Haley et al. 2016; Williams et al. 2012; Williams et al. 2014; Williams, Haley, and Jones 2015).

EP has two primary components, demand side and supply side, with the former calculating energy demanded (e.g., kWh electricity and million British thermal units [MMBtu] natural gas) by different services (e.g., building space heating and VMT), and the latter determining how each energy demand is met (e.g., natural gas extraction, power plants, and distribution wires). Operationally, this distinction is important in the model because the demand and supply sides are calculated in sequence and without iteration, as decisions on the demand side do not depend on cost. This section focuses on the calculations and inputs for the demand side, the outputs from which are the focus of this report.

5.1 Sector Representations, Data, and Assumptions

The demand side of EP starts with macroeconomic, demographic, and climate-related inputs (e.g., population or heating-degree day projections) that drive increases or decreases in the demand for energy services over time. The variables become the backbone on which the rest of the model calculations depend and are the basis for forecasting future demand for energy services. For example, when calculating the weight of laundry washed in residential households annually, a 10% increase in the demand driver (number of households) will result in a similar increase in the service demand (weight of laundry).

Technology stocks that satisfy each service demand are tracked over time using an annual stock-rollover. The composition of the stock over time will depend on the technology lifetimes and the sales shares stating which technology replaces another upon retirement or stock growth. These sales shares are explicit user inputs and are the mechanism by which the different electrification adoption scenarios are created (see Section 4.1). EnergyPATHWAYS helps the user understand the implications of any technology or infrastructure decisions by linking this decision with the rest of the energy system with high fidelity. Default initial year stocks and sales shares are calibrated to empirical data, but the model does not then endogenously solve for investment decisions.

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[42] "EnergyPATHWAYS" https://github.com/energyPATHWAYS/EnergyPATHWAYS.

The composition of the stock along with the service efficiency of each technology is used in calculating energy demand. Service efficiency of each technology depends on that technology's vintage and may change over time. Changes in technology cost and performance come from a variety of public sources, including the prior publication in the EFS series (Jadun et al. 2017). At times, a technology will be allocated a smaller or larger share of service demand; for instance, electric heaters typically have a smaller load and electric vehicles with shorter ranges drive fewer annual miles. In vehicles, allocation of service demand to stock also depends on technology age with newer vehicles driving more miles. In other cases, each technology receives a share of service equal to its share as a stock, for instance all residential cooking technologies have equal service regardless of fuel type.

Total energy demand can be calculated by dividing service demand by service efficiency and summing across each service demand category, which are referred to as demand subsectors in the model. The demanded energy will be in one of many different fuel types (e.g., electricity or natural gas) depending on the technologies deployed and will be specific to a geography and customer class. Electricity demand is unique in that it also gets allocated to the time of year using normalized hourly demand profiles, which are explained in the next section. Each of the calculation steps described are shown in Figure 5.1.

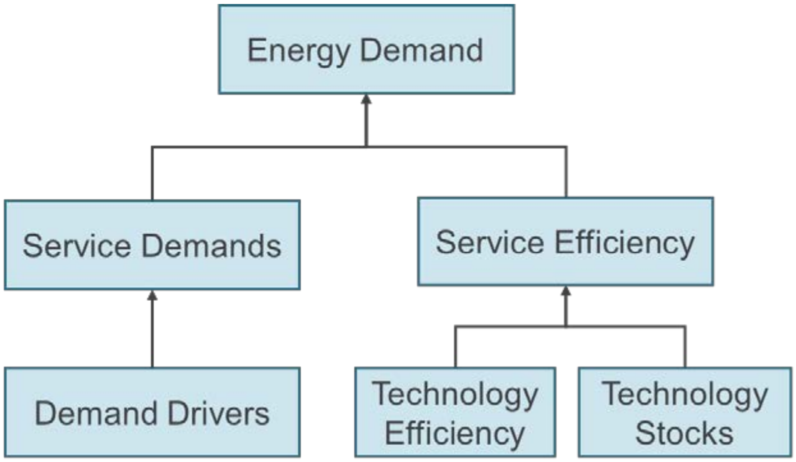

Figure 5.1. Data flow in the EnergyPATHWAYS model

A variety of data sources are used to describe the reference energy system and characterize different energy technologies. On the demand side, most of these come from the EIA's Annual Energy Outlook (AEO), which is produced with the National Energy Modeling System (NEMS). EP uses both inputs from NEMS and, also its macroeconomic outputs (primarily from the AEO2017 Reference case), to establish the baseline data used in many of the modeled scenarios. Industry, except for fossil extraction and refining, is exogenously determined by the NEMS Macro-Economic Module (MEM). Fossil and refining energy demand is determined endogenously. The full list of data sources applicable for this study and technologies deployed are provided in Appendix E.

5.2 Electricity Consumption Patterns

We describe above the process by which annual energy consumption is calculated for each demand subsector by fuel type and location. To produce annual load profiles, unitized (normalized to one) annual hourly load shapes specific to a geography and technology, subsector, or sector are multiplied by annual energy demand as illustrated in Figure 5.2. Distinct unitized shapes are used for 33 different subsectors or technologies, most of which are in buildings. For end uses without an explicit shape, a geography-matched 2012 historical system load is used. Detailed information on the complete list of shapes are provided in Appendix E.

The native geography of each shape varies. For some, a unitized profile represents the shape of service demand across the whole United States (e.g., for residential dishwashing). And for others, a much higher resolution is available (e.g., HVAC technologies where profiles vary by International Energy Conservation Code [IECC] climate zone within each state).

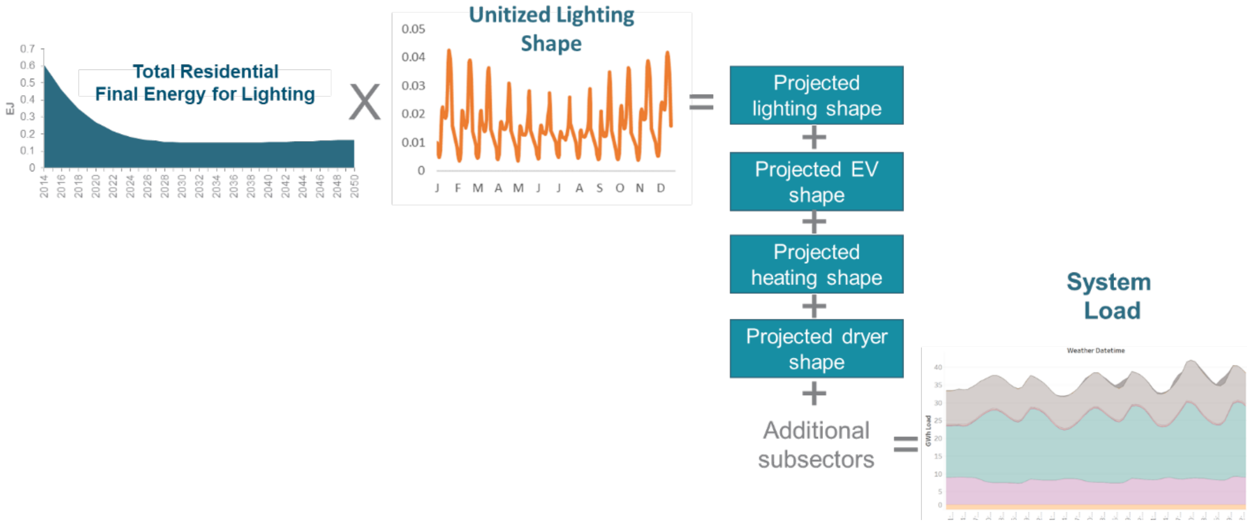

Figure 5.2. Method of estimating electricity consumption in the EnergyPATHWAYS model

Illustration by Evolved Energy Research

The final step to create load shapes (not shown in Figure 5.2) is a reconciliation step between the estimated bottom-up load shape, which uses weather from 2012, and the known historical hourly system load shape from 2012 Federal Energy Regulatory Commission (FERC) utility data. Correction factors are created by dividing the top-down historical shape by the bottom-up estimated load shape. Bottom-up load shapes are then multiplied by 2012 factors to get a final estimate of bottom-up load for years post 2012. The need for reconciliation largely stems from a lack of adequate temporal and spatial granularity in the unitized profiles, details for which are provided in Appendix E. Depending on how the profiles are used, applying the reconciliation can help more faithfully reproduce peak loads, hourly ramps, and variability in daily energy consumption.

Although the load shape estimation method in EP has its limitations (see Section 5.4), it enables a first-order estimate for how electrification or other demand-side transition scenarios might impact electricity consumption patterns. Section 7 presents the electricity consumption results, and a future EFS study will include further modeling to evaluate how hourly electricity demand profiles might be affected by electrification.

In addition to its construction of bottom-up load shapes, EP has a representation of flexible load. The flexibility of newly electrified loads (e.g., electric vehicles) to shift in time cannot be ignored in a discussion of demand-side load shape impacts. Flexible load is solved on the supply side of EP within a least-cost electricity dispatch. Demand-side flexibility, as modeled for this analysis, includes only load shifting as described below. It does not include other grid services that could be provided from the demand side; we do not include the provision of ancillary services or firm capacity services that could be provided by end-use electric equipment. Moreover, we examine only the limited range of demand-side flexible options described below. As a result, this incomplete coverage and the fact that any evaluation of impacts of the demand-side flexibility would require supply-wide analysis (which is outside the scope of this report), flexibility is given limited treatment within this report.

Within EP, flexible load energy must be balanced in the electricity dispatch over different timescales. The flexibility to shift energy throughout the day is determined by inputs describing the number of hours that service for a given end use can be shifted either forward or backward in time and the decision to do so is determined within the optimization to minimize the cost of serving load. The assumptions for the subsectors where flexible operation was explored are presented in Table 5.1. The technologies represented here are not exhaustive, and they ignore both industrial and additional building loads that may be able to provide flexibility but that were not explored.

A passenger LDV with five hours of load delay and zero hours of load advance means that, relative to a counterfactual case where charging starts immediately after the vehicle is plugged in, the vehicle can wait for up to five hours to begin charging. An HVAC system with one hour of load delay and one hour of load advance can move load either backward in time by waiting to provide service or forward in time by pre-cooling/heating. In addition to the number of hours load can be shift in time, the percentage of total that has flexible load enabled is shown in Table 5.1. Results from these scenarios are presented in Section 7.

Table 5.1. Default Load Flexibility Parameters

Subsector	Hours Delay	Hours Advance	Base Scenario (% flexible)	Low Flexibility (% flexible)	Enhanced Flexibility (% flexible)
Light-Duty Vehicles	5	0	2015: 50% 2050: 75%	2015: 50% 2050: 50%	2015: 50% 2050: 90%
HVAC (commercial)	1	1	0%	0%	2015: 0% 2050: 25%
HVAC (residential)	1	1	0%	0%	2015: 0% 2050: 35%
Water Heating	2	2	0%	0%	2015: 0% 2050: 25%

The starting-point (2015) flexibility for LDV charging is meant to approximate the flexible charging already observed today, incented by time-of-use charging rates.

5.3 New Modeling Capabilities

Several new capabilities in EP were developed for the EFS study. In this section, we summarize these capabilities, which are not described in either the model documentation or published reports that have relied on EP.

Industry Model Enhancements

Before the origination of the EFS, EP did not have technology detail on the demand-side for industrial sector. This meant we could not comprehensively model electrification in industry in the same manner as for other sectors, i.e., with assumed technology penetrations, stock rollover, or other variables. To address this limitation, we decomposed industrial energy use for end uses that were determined to be electrifiable: space heating, boilers (i.e., steam production), process heating, and machine drives.

We defined nearly all electrification of industry to occur at the end-use level with the substitution of electricity for existing combustion fuels and not at the level of technologies applied to specific processes.[43] We introduced additional modeling detail by decomposing the end-use energy of certain industries down to the process level and by characterizing representative electrotechnologies whose technical assumptions are constant across all industries. We have assumed process heating end-use energy for the wood products and printing and related support industries can be characterized at the process-level as curing. We have also assumed all process heat end-use energy in the plastic and rubber products industry can be characterized as drying.

The technologies modeled for industry (electric machine drives, industrial heat pumps, induction furnaces, infrared heating, resistance heating, ultraviolet heating, and electric boilers) do not have technical characteristics that vary by industry and process due to a lack of process-level energy and technology data. Instead, each technology represents the substitution of electricity for combustion fuel based on assumed efficiencies. For example, we assume induction furnaces represent electrification of process heating end-use energy in transportation equipment manufacturing, and industrial heat pumps represent electrification of process heating end-use energy in chemicals manufacturing and food manufacturing.

For each end use and the curing and drying processes, we developed a service demand and equipment stock representation to replace the simple annual projections of energy demand previously based directly on AEO2017 industry value of shipments. The steps to this process are as follows:

1. Establish a set of representative technologies that have the same technical characteristics regardless of the adopting industry. Technology characteristics include efficiency,

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[43] Further characterizing end uses by including temperature requirements would improve the resolution of our analysis. However, without a characterization of U.S. industrial heat demand—analogous to analysis performed for the European Union and many of its member states (Naegler et al. 2015; McKenna and Norman 2010; Werner 2006)—we chose not to pursue this modeling expansion. We do note that studies have characterized industrial waste heat (DOE 2016; Elson et al. 2015; Thekdi and Nimbalkar 2014).

lifetime, and typical utilization factors for all end uses as well as capital costs for space heating and boilers.[44]

2. Calculate projection of service demand. Service demand estimates are derived from input projections of equipment stock efficiency and energy demand.
3. Develop estimates of equipment initial stock by combining projections of service demand by representative technology with the utilization factor of technologies.
4. Run a stock flow model starting with the initial stock and accounting for new technology sales shares over time.
5. Calculate final energy demand by dividing the allocated service for each technology by that technology's service efficiency.

These baseline stock compositions, combined with service demand projections, created a framework for calculating both the pace and impact of the adoption of electrotechnologies in specific industrial end uses.

Data Updates from the Annual Energy Outlook 2017

Energy projections for all subsectors, demand drivers, and technology cost and performance assumptions have been updated as part of the EFS to reflect the AEO2017 Reference case (EIA 2017c). In several cases, the technology cost and performance assumption in EP have been updated as part of the EFS to have more granularity than NEMS, as described below. Details are provided in Appendix E.

New Technologies Modeled

As part of the EFS, residential electric heating was subdivided into ducted and non-ducted components with reference technologies for electric furnaces and baseboard electric heaters, respectively. In the modeled scenarios with increased electrification, these technologies are replaced over time with ducted air source heat pumps or mini-splits, which provide energy efficiency benefits.

In the light-duty car and truck subsectors, new technologies have been added to reflect the higher vehicle granularity in ADOPT. Most notably, a single battery electric vehicle technology has been divided into three vehicle types with ranges of 100, 200, and 300 miles, each with specific cost and performance assumptions. Each electric vehicle technology also has its own derate to the allocated service demand based on vehicle range—the shorter the vehicle range, the fewer miles it is assumed to drive annually relative to the reference vehicle. We also acknowledge here the potential for significant improvement in battery range given recent improvements in some offerings from manufacturers.

Also, as part of the EFS, the electric bus transit subsector was added along with all major bus types. This transit subsector is one component of buses as a whole, which also includes intercity buses where electrification was not considered as part of this study.

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[44] Due to data availability, costs were included only for technologies that were also represented in the commercial sector (e.g., boilers and furnaces). In those cases, costs were equivalent between the commercial and industrial sector.

Electric Vehicle Infrastructure Cost

The installation costs for new PEV charging equipment and the maintenance cost have been updated to better reflect the cost and need for building charging infrastructure (Jadun et al. 2017). PEV charging costs are divided into two components: the grid-upgrade costs of new home wiring (which is not re-incurred for each subsequent EV) and the cost to replace the home PEV charger itself (which is periodically re-incurred). Total vehicle and charging infrastructure maintenance costs are based on Jadun et al. (2017).

Efficiency by Climate Zone for all Heat Pumps Used for Heating or Cooling

Another important advancement in EP data made through the EFS has been to specify the service efficiency by IECC climate zone for all residential heat pumps and air conditioners used for space and water conditioning. Performance of commercial HVAC equipment was not assumed to vary by climate based on a review of building simulation outputs. Before this update, a single efficiency value was used across the United States, which overstated the efficiency of heat-pumps in very cold climates. The efficiency trajectories were adjusted to reflect anticipated advancement in cold-climate heat pumps.

5.4 Caveats and Limitations

As an accounting framework, EP has limitations that should be acknowledged to appropriately interpret the results. The limitations of the overall study approach are discussed in Section 4.3, but further disadvantages with respect to EP are discussed here. One of the largest limitations is that technology adoption is an exogenous input and does not depend on relative technology cost effectiveness or consumer choice. Instead, exogenous analysis has informed these adoption shares. Differences in methodology between sectors for estimating these adoption shares makes it difficult to directly compare electrification ambition between each sector.

Additionally, as a bottom-up accounting model, EP lacks feedbacks of many kinds that are found in macro-modeling frameworks. For instance, the model has no demand elasticity and does not solve for economic equilibrium. This means energy demand is not updated based on cost—thus, service demand is not reduced when costs increase and vice versa. Furthermore, industries outside of energy extraction (e.g., cement, bulk chemicals, fabricated metal products) have final energy demand exogenously specified and do not depend on decisions happening elsewhere in the modeling. The net result is that while the model accounts for energy and cost flows in sophisticated ways, some activities in the economy may be mutually inconsistent and it is up to the user to achieve consistency through off-line analysis and explicit updates to inputs.

In addition, the definitions and modeled operations of different technologies is necessarily stylized and aggregated. Even at a state level, EP cannot capture important geographical nuances and by always modeling the “average” technology and household, important insights about opportunities or distributional impacts are lost. EP also misses some cross-correlation in buildings that could be meaningful. For instance, customers most likely to adopt heat pumps may have building shell efficiencies that are higher than the average, and these second-order effects cannot be captured without representations of individual households.

The modeling of flexible load in EP also has important limitations. First, the type of load shifting modeled is still in a pilot stage in most cases, and the maturation of this technology over the decades modeled is not guaranteed. EP dispatches flexible load optimally from a total system cost perspective, and the need to send the necessary signals to individual customers to achieve this may limit the impact of flexible load in practice. Flexible load also is dispatched with perfect foresight; thus, forecast error and lead-time for scheduling is ignored. Finally, flexible load is constrained by cumulative energy requirements across an equipment population. This is less constraining than modeling individual pieces of equipment separately and then aggregating the impact across the population.

Although it is important to acknowledge these caveats and limitations in the EP modeling analysis conducted for this report, EP enables a detailed bottom-up approach for numerous end uses and technologies across all major subsectors in the U.S. energy economy. This capability is applied to isolate and assess the impacts of widespread electrification in the EFS.

6 Results: End-Use Stock and Service

The rate of an energy transition is determined by both the adoption rate and the inertia in the system from the built-in advantages of incumbency. In this section, we present the overall equipment stock transformation and service demand provision results from the electrification adoption scenarios. In particular, the sales shares (presented in Section 4) are input to the EP model (described in Section 5), which calculates the new equipment stock based on changes in service demand and equipment turnover assumptions.[45] EP also estimates the service demand provided by different technologies and fuels as well as energy and electricity consumption. This is accomplished for each technology modeled, end-use, and region.

Figure 6.1 illustrates this process for commercial building space heating under our High electrification (and Moderate technology advancement) scenario. The first panel (Sales) shows how the assumed sales share of electric heating technologies (both electric resistance-based and heat pump technologies combined) grows to 71% by 2050 in this scenario. Based on the expansion of new buildings construction (1.1 billion square feet per year from 2015 to 2050) and assumed equipment lifetimes,[46] this sales share is equivalent to 771,000 units sold in 2050 and a stock of 11.7 million units (64% of stock) in that year as shown in the second panel (Stock). For this High electrification scenario, electric heating technologies are estimated to provide 59% (800 $\text{MMBtu}_{\text{heat}}$)[47] of commercial space heating in 2050 compared with 41% for other, primarily natural gas-based, technologies as shown by the third panel (Service Demand). The assumed efficiencies of the full suite of heating technologies (including combustion-based, electric resistance, and heat pump technologies) impact energy and electricity consumption. The last panel of Figure 6.1 (Energy) shows how the increasing use of efficient ASHPs reduces overall final energy use for commercial space heating from about 1.6 quads in 2017 to about 1 quad in 2050 despite an overall growth in heating service demand. Commercial heating from electricity grows from 6% in 2017 to 33% in 2050 in final energy terms across the contiguous United States, despite heating service demand served by electricity increasing to 59% by 2050, which demonstrates the energy-saving effect of the greater energy efficiency of electric heat pumps.

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[45] We do not assume any premature retirements of equipment in any scenarios. Assumptions about equipment lifetime and service demand growth are the same in all scenarios.

[46] Average lifetimes are specified by technology and range from 14 years for heat pumps to 17.5 years for furnaces and 25 years for boilers. Each technology also has a unique standard deviation on lifetime that impacts the shape of technology retirement.

[47] Heat pumps comprise approximately 64% of all electric heating technologies with the remaining 36% a mix of electric furnaces, electric boilers, and electric baseboard radiators.

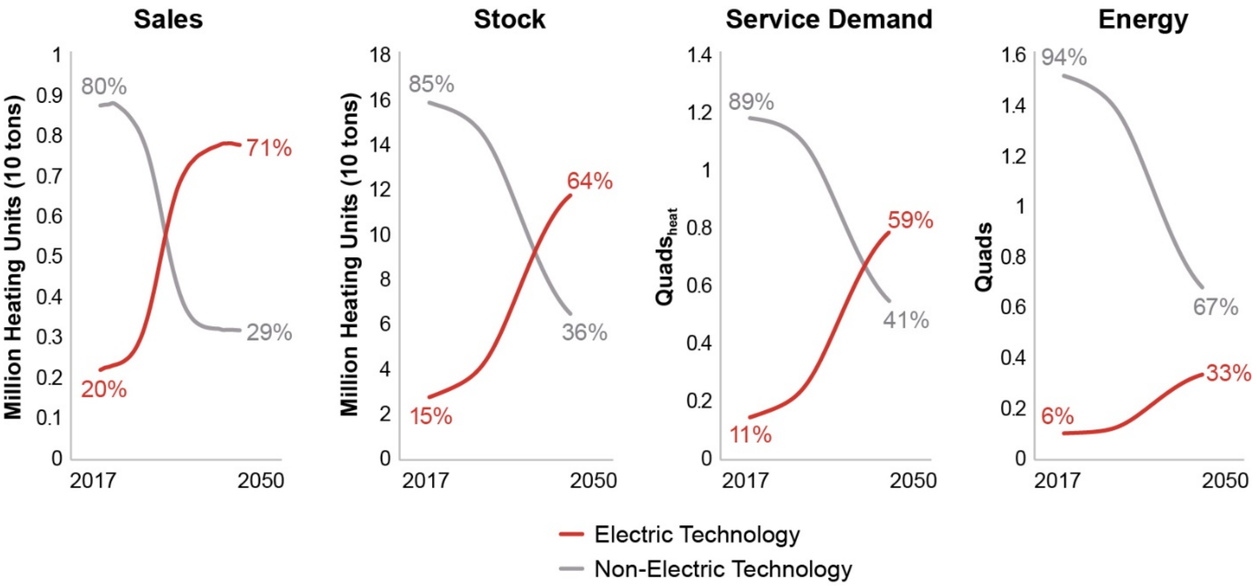

Figure 6.1. Commercial buildings space heating evolution in the High scenario

The steps and dimensions illustrated by Figure 6.1 for commercial space heating are applied similarly for all end uses, technologies, and scenarios.[48] Figures 6.2–6.6 present the stock and service demand results for select technologies in the transportation, buildings, and industry sectors in the three core electrification scenarios.[49] Results for other technologies and sectors are available for download at www.nrel.gov/efs.

6.1 Transportation

Figure 6.2 shows the modeled on-road vehicle stock and Figure 6.3 shows the share of transportation services (VMT) by fuel type for the core electrification scenarios. In the Reference scenario, which is consistent the AEO2017 Reference case, PEV adoption is largely restricted to only the LDV subsector and PEVs reach 18 million by 2050. Although this represents a substantial increase from the U.S. PEV fleet in 2016 (560,000 PEVs estimated by IEA 2017), it represents only 11% of all light-duty cars and trucks in 2050.[50] Outside the light-duty passenger car sector, PEV adoption is very limited, as shown in Figure 6.2. In terms of service demand, electric VMTs make up a smaller fraction (8.3%) of total VMTs under the Reference scenario because PEVs are assumed to drive fewer annual miles.[51]

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[48] Representation for the industrial sector differs somewhat due to the limited data estimates of equipment lifetime among other key factors. Section 5 describes the industry representation.

[49] The figures show stock and service results only, which, based on our methodology, are unaffected by the technology cost and performance assumptions. Therefore, the results apply to all technology advancement—Slow, Moderate, Rapid—projections.

[50] In 2016, new PEV registrations in the United States totaled about 160,000. Globally, IEA (2017) estimates about 750,000 new PEV registrations in 2016 and a stock of about two million electric cars.

[51] Representative VMTs vary by vehicle type and age based on regressions of data from the Energy Information Administration (see Appendix E). EP uses an exponential decline in VMT with vehicle ages. In addition, we assume VMT per PEV varies with battery range based on data from Melaina et al. 2016.

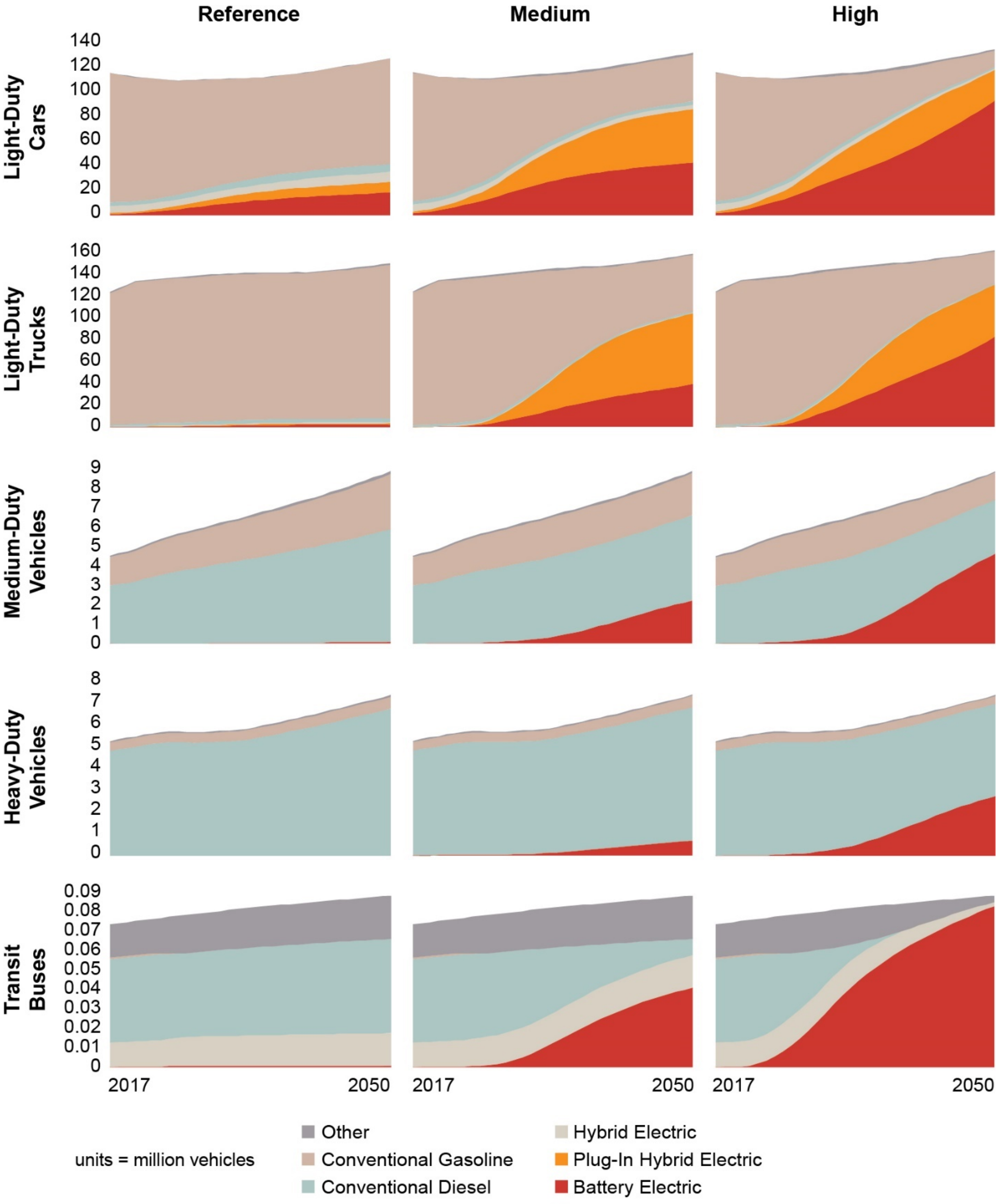

Figure 6.2. Vehicle stock in the electrification scenarios

Multiple vehicle types, with different battery ranges, are modeled for light-duty PEVs, but they are grouped together for the figure.

More PEVs are found in the Medium and High electrification scenarios. In the Medium scenario, PEVs comprise a sizeable share of the 2050 LDV stock (186 million light-duty PEVs, 66% of all LDVs), but they are more limited in other transportation subsectors where transformations have been shown to be harder due to vehicle requirements and economic considerations (Muratori et al. 2017). In the Medium scenario, a majority (57%) of PEVs in the light-duty fleet (cars and trucks) are plug-in *hybrid* rather than BEVs, according to the ADOPT modeling used for this scenario (see Appendix B). These results stem from the challenges associated with electrifying larger vehicles, including battery size, weight, volume, range, and charging duration. Many of these challenges are assumed to remain to some extent in the Medium scenario. As a result, PEVs comprise 25% of 2050 MDVs (2.2 million trucks) and 9% of HDVs (660,000 trucks) in that scenario.[52] Although interest in electric trucks has grown in recent years as demonstrated by plans from ports in Southern California and new model announcements by manufacturers (Port of Long Beach and The Port of Los Angeles 2017; Ayre 2017), in the Medium scenario large electric trucks are restricted to short distance applications and niche markets only. They do not achieve widespread adoption for long-haul uses, which reflects some of the higher barriers for electric trucks in such applications. However, even for long-haul freight delivery, there may be conditions where electric trucks would be favored. For example, tightened emissions regulations at state, local, or federal levels (e.g., increased efficiency standards and low-emissions zones)[53] and development of an advanced charging infrastructure (e.g., inductive or catenary charging) could promote adoption of electric long-haul trucks. Despite having some of the same size and weight challenges as large freight trucks, battery electric buses have other characteristics—such as regular and short routes, and urban air pollution benefits (Mahmoud et al. 2017)—that are more conducive to electrification. In the Medium scenario, 46% of the 2050 transit bus fleet is estimated to be comprised of battery electric buses.

In the High electrification scenario, many of these barriers are overcome and electric vehicles make up the majority of the on-road fleet. In particular, 88% and 81% of light-duty cars and trucks, respectively, on U.S. roads in 2050 are PEVs in this scenario. Of these PEVs, the majority are estimated to be BEVs. In this scenario, nearly all (94%) buses are electric. Electric trucks also play a prominent role with 52% of all medium-duty trucks and 37% of all heavy-duty trucks relying on electric motors as the primary powertrain. VMT shares by fuel follow similar trends in the High electrification scenario (Figure 6.3).

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[52] All PEVs in the medium- and heavy-duty subsectors are assumed to be all-electric. Plug-in hybrids are not considered in the medium- and heavy-duty subsectors in this analysis due to scope limitations and lack of data.

[53] BEVs have zero tailpipe emissions and electric HDVs have lower lifecycle emissions than diesel technologies in most regions, depending on the electricity grid mix (Sen, Ercan, and Tatari 2016).

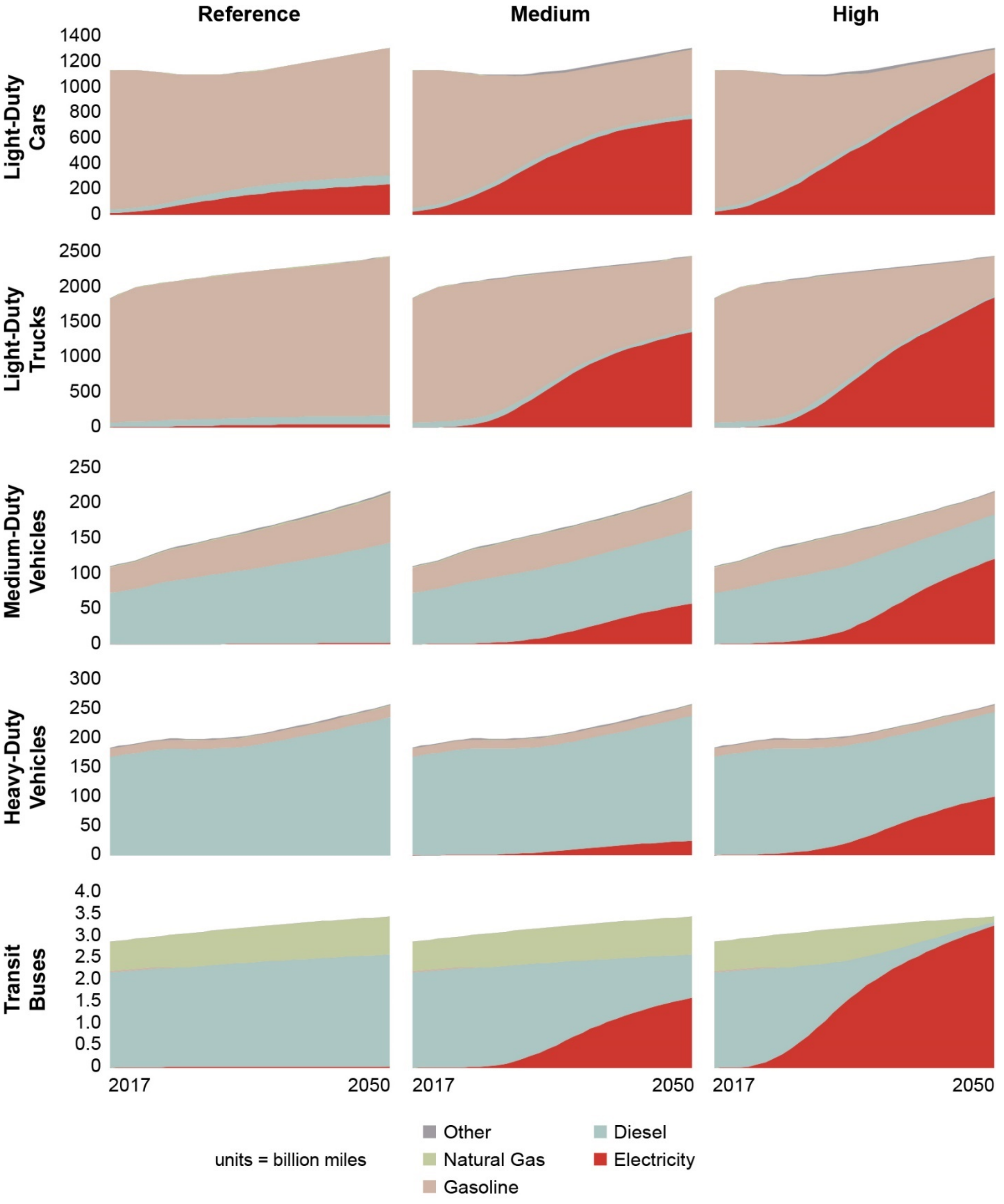

Figure 6.3. Transportation service demand by fuel type in the electrification scenarios

Other fuels include compressed natural gas, liquefied natural gas, and hydrogen.

Figures 6.2 and 6.3 provide the numerical stock and service results to help characterize the electrification scenarios, which are developed primarily using an accounting framework (Section 5). Here, we provide additional discussion related to technological considerations and infrastructure requirements with increased electrification in transportation that are not fully captured in the modeling. To the extent that widespread transportation electrification—such as that envisioned in both the Medium and High electrification scenarios—is driven by economics, continued advancements in battery and charging technologies that maintain or improve performance while lowering costs will be required. Improvements to battery technologies include increasing energy density to meet weight and volume requirements of vehicles while increasing travel ranges between charges and enhancing reliability to maintain performance over numerous cycles, years, and weather conditions.

Current research efforts to improve charging technologies and networks also exist, and success in these areas is likely needed to enable the levels of electrification in the Medium and High electrification scenarios. Two key areas of needed improvement in actual vehicle charging are speed (reducing battery charging times) and coverage (having adequate and accessible charging stations). Current commercially available charging technologies include direct current fast chargers (DCFCs) and Level 2 (L2) chargers, both of which can reduce charging times dramatically from standard Level 1 (L1) home charging (SAE 2012).[54] However, installation costs can be significant, particularly for DCFCs, and long charging times might create barriers for some uses or discourage PEV adoption to some drivers. Conversely, an advantage of PEVs is that charging can potentially occur at various locations, including in home, in workplaces, and at public charging stations, whereas conventional vehicle refueling is often restricted to gas stations. Other charging options that are under development but not available in the current market, and which are potentially most applicable for fleets or freight, include catenary charging, inductive or wireless charging, and battery swapping (Lukic and Pantic 2013; Mak, Rong, and Shen 2013).

Coverage considerations include geographic distances between charging stations, number of plugs in each station, driving behavior, charge time, and differences between different driving populations and regions (e.g., cities, towns, rural areas, and interstate corridors). Wood et al. (2017) provide a national-level assessment of charging infrastructure requirements. Another important consideration is the universality of charging networks (i.e., whether drivers can access networks with different charging technologies, owners, or operators, and at what costs).

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[54] L1 charging refers to using an ordinary (120 V in the United States) household outlet. L2 charging supplies higher voltage (240 V) electricity to reduce charge time. Charger power ratings are also important factors. Jadun et al. (2017), which is used in the EFS, assumes 50 kW for light-duty PEVs and 350 kW for medium- and heavy-duty PEVs. IEA (2017c) provides additional discussion and outlooks for electric vehicle supply equipment.

A detailed examination of the issues regarding battery technologies, charging technologies, and infrastructure networks is outside the scope of our analysis. However, in addition to the qualitative considerations described above, which highlight the complexities associated with widespread transport electrification, we consider vehicle charging in a limited extent in our analysis. In particular, infrastructure costs, developed by Jadun et al. (2017), are factored into the EP scenarios and impact overall system and household costs to be reported in future reports. Future analysis in the EFS will also consider how vehicle charging profiles can impact electric infrastructure development and system operations.[55] Moreover, Text Box 6.1 presents approximate charging infrastructure needs for the light-duty fleet estimated in the electrification scenarios.

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[55] For an overview of these topics see, for example, Denholm and Short (2006), Duvall et al. (2007), Clement-Nyns, Haesen, and Driesen (2010), and Muratori (2018).

Text Box 6.1. PEV Charging Infrastructure Needs in the Electrification Scenarios

Transitioning from liquid fuels to electricity in the on-road transportation sectors will require a significant change in how the “fuel” is delivered to the vehicles. The required electric vehicle charging infrastructure, also known as electric vehicle supply equipment (EVSE), will depend on a variety of factors, including the vehicle mix (battery ranges, hybrid and non-hybrid vehicles, fuel economy), environment (cities, towns, rural areas, interstate corridors), consumer preference and charging behavior, and technology evolution (e.g., use of direct current fast chargers). Fully assessing these factors is beyond the scope of the EFS; however, in this text box we provide an approximate estimate of non-residential EVSE that would be needed to support the 2050 *light-duty* PEV stock in the electrification scenarios based on findings from Wood et al. (2017).

Wood et al. (2017) provide rich detail in terms of EVSE requirements, including several sensitivities about consumer and vehicles attributes. Here, we simply apply typical charging station-per-EV (and plug-per-PEV) ratios based on their Central Scenario, which finds that on average 0.57 DCFC stations (and 1.85 plugs) and 40 non-residential L2 plugs per thousand PEVs would be needed to provide minimum coverage requirements. Applying these factors to the estimated light-duty PEVs (both cars and trucks) in our scenarios provides an estimate of non-residential 2050 EVSE needs:

Electrification Scenario	**DCFC**		**Non-Residential L2**
	Stations	**Plugs**	**Plugs**
Reference	17,000	55,000	1,200,000
Medium	106,000	343,000	6,110,000
High	138,000	447,000	9,980,000

For comparison, by the end of 2017, there were approximately 55,000 stations/outlets, about 80% of which are L2 (EV Adoption 2017; AFDC 2018). These simple estimates are intended to provide a rough approximation of infrastructure requirements, and there are several limitations with this method. First, we extrapolated the results from the Central Scenario from Wood et al. (2017), which includes 15 million PEVs that are mostly charged at home. The type, number, and location of PEVs differ in our scenarios; therefore, it is unclear whether the calculated ratios apply. For example, in a recent report (Bedir et al. 2018), the same approach used by Wood et al. is applied to estimate charging requirements in California, showing higher charging requirements per vehicle. Second, Wood et al. acknowledge multiple uncertainties and estimate infrastructure needs under a range of sensitivity cases showing significant variations. We do not consider those sensitivities. Third, the analysis from Wood et al. focuses on LDVs only, while our scenarios include substantial adoption of electric MDVs, HDVs, and buses. As a result, total charging infrastructure needs in our scenarios are greater than needs presented in this text box. Lastly, the estimates do not consider significant changes in driving behavior or technological disruptions. Examples include increased utilization of transportation network companies (e.g., ride-share companies) and autonomous driving, which might increase infrastructure requirements through greater VMTs or reduce requirements through more-optimal use of vehicles and charging networks.

6.2 Buildings

In the buildings sector, electrification in our scenarios has the biggest impact on three end uses for both residential and commercial buildings: space heating, water heating, and cooking. Final energy consumption for these three end uses, combined, made up 46% of total (commercial and residential) buildings sector energy use in 2015 (EIA 2017c). Figures 6.4 and 6.5 show the 2050 equipment stock and service shares for these end uses and for the mix of technology types considered across the core electrification scenarios. Electricity is a common source of energy in nearly all buildings technologies, and electric technologies are often used to provide heating and cooking today. In the Reference scenario, we estimate electric technologies will grow to provide 18% and 15% of 2050 space heating needs in residential and commercial buildings, respectively. Most of these heating services are from ASHPs, which comprise 40% and 54% of all electric heating units in residential and commercial buildings by 2050.[56] Figures 6.4 and 6.5 also show the small share of electric water heaters (including heat pump water heaters) and electric cooktops (including induction and resistance stoves) in the Reference scenario.[57]

Despite the measurable degree of buildings electrification in the Reference scenario, we assume significant expansion of electric buildings technologies in the Medium and High electrification scenarios, particularly with respect to heat pumps for both space and water heating. Under the Medium scenario, ASHPs together with electric furnaces and other electric resistive heating equipment, provide a slight majority (40%) of residential space heating needs by 2050. Similarly, for commercial buildings, electricity-based technologies—particularly ASHPs—grow to provide approximately 35% of space heating services. Electric technologies are also assumed to achieve substantial growth for water heating, cooking, and clothes drying. In the Medium scenario, electric shares of water heating grow to 47% and 20% in the residential and commercial sectors, respectively. Electric technologies for cooking grow to 71%, and 60% in the residential and commercial sectors, and residential clothes drying achieves almost complete market share (98%) by 2050, as shown in Figures 6.4 and 6.5.

In the Medium and High electrification scenarios, ASHPs replace both non-electric technologies and the incumbent electricity resistance technologies. The replacement of electric resistance with ASHPs has a strong energy efficiency impact that leads to declining overall electricity consumption in certain sectors (e.g., residential water heating) and regions (e.g., Southeast) where Reference shares of electric resistance are large. In these cases, total energy consumption declines even though the share of service demand provided by electric technologies increases. Section 7 presents and quantifies the energy and electricity use results from the scenarios.

Despite the substantial growth in electric technologies, reliance on non-electric technologies, particularly natural gas-based technologies, remains sizeable in the Medium and Reference scenarios due to incumbency and economic advantages. For example, residential furnaces have

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[56] Other electric heating technologies include electric furnaces, electric resistance heaters, electric boilers, and ground source heat pumps. We note that the number of units will depend on multiple factors, such as the unit capacity, building layout, and technological progress.

[57] Our Reference (and Medium and High) scenarios all assume the same fixed level of end use service consumption based on the AEO2017 Reference case. As a result, we do not consider any substantial structural shifts in the economy or changes in consumer behavior outside those represented in the AEO2017 Reference case that could impact service consumption—such as dramatic shifts towards multifamily housing.

typical lifetimes on the order of 15 to 20 years. Given that residential heating systems are typically only replaced following system failure, only two opportunities (two life-cycles) exist for new electric-technologies (e.g., heat pumps) to replace incumbent technologies over the present day to 2050. Furthermore, in cold-climate regions, the lower efficiencies of conventional heat pumps and higher upfront capital costs of cold-climate optimized heat pumps (relative to conventional technologies) decrease the economic competitiveness of heat pumps in those regions, and they challenge the potential for widespread adoption in colder climates.[58] Finally, challenges associated with building retrofits (including the potential need for new ducting and upgraded electric service), installer or contractor experience (and level of comfort with heat pump technologies), access to capital, and consumer preferences may also hinder the spread of electric technologies in the buildings sector.

For the High scenario, we assume many of these challenges or barriers to adoption are overcome and electric technologies become pervasive in nearly all U.S. buildings. For space heating services, we assume cost and performance improvements in heat pumps lead to substantial economic advantages of heat pumps in moderate climates; and, we assume successful R&D drives down the life-cycle cost of cold climate heat pumps, through advances in compressor technologies, refrigerants, and defrost cycling, as well as through development of potential non-vapor compression technologies (Baxter and Groll 2017a, 2017b; Shen 2017; Korn, Walczyk, and Jackson 2017; Messmer 2015), allowing cold climate heat pumps to be cost-competitive with conventional technologies. Under the High scenario, heat pumps deliver 35% of end-use service demand in cold-climate residential and commercial buildings by 2050. Similarly, we assume successful R&D and deployment programs lead to improvements in the cost, performance, and social acceptance and familiarity with heat pump water heaters, such that 38% of water heating services is met with electric appliances in aggregate across the residential and commercial sectors. Finally, improvements and cost reductions in electric cooking appliances lead to nearly universal market share of cooking applications—cooking services are 90% electric across the buildings sector by 2050 in the High scenario.

The High scenario would require a substantial expansion of both the ASHP supply chain (domestic or international) and installation capacity. Under this scenario, 107 million residential units and 9 million commercial units are installed by 2050.[59] Increases in other electric buildings technologies are also substantial (see Figure 6.4).

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[58] Some cold climate regions, such as New England, remain substantially dependent on high-cost fuel oil for heating applications. As a result, despite the higher upfront cost and lower (but improving) efficiency of cold climate heat pumps, we assume heat pumps do increase their share of space heating demands in these regions because of their improved competitiveness relative to high fuel cost options.

[59] We note that the number of units will depend on multiple factors including, most importantly, the unit capacity. Residential heat pumps have a typical capacity of 36 thousand British thermal units (kBtu) per hour and we assume 120 kBtu per hour for commercial heat pumps to estimate number of units.

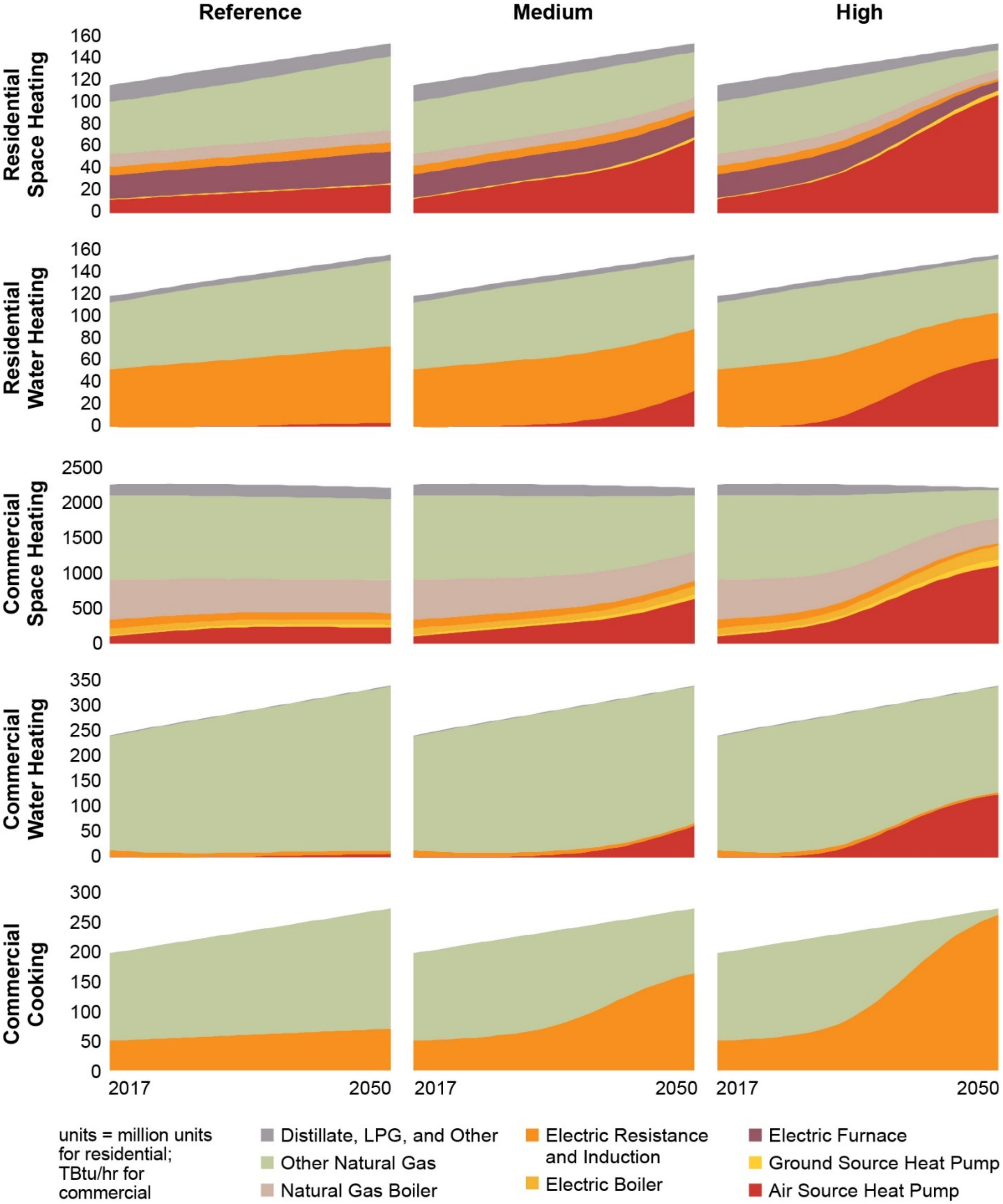

Figure 6.4. Buildings equipment stock in the electrification scenarios

EP models several technologies for each end-use service.
These technologies are grouped into categories in the figure for convenience.

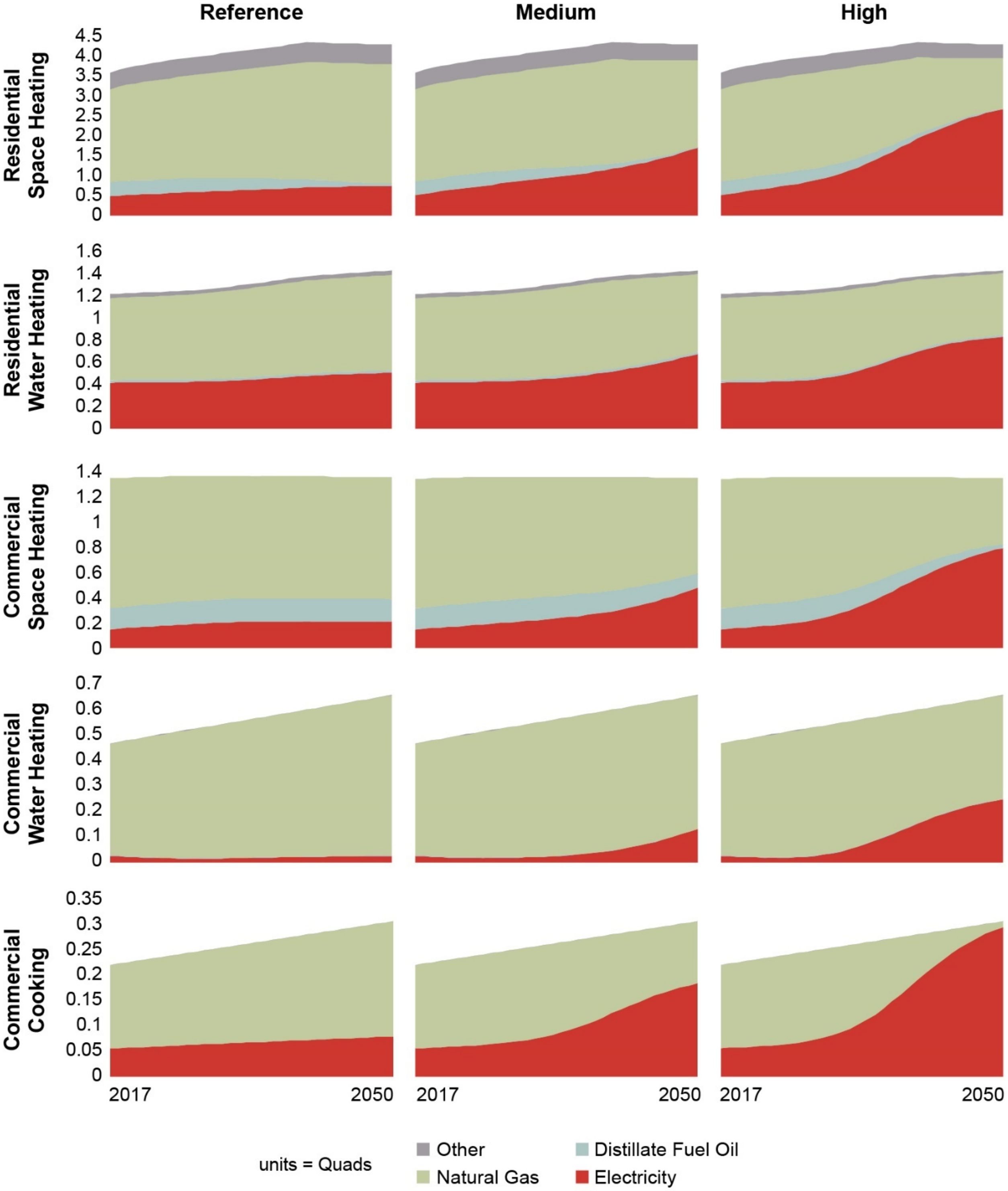

Figure 6.5. Buildings service demand by fuel type in the electrification scenarios

"Other" fuels primarily include propane and biomass wood.

Figures 6.4 and 6.5 provide the numerical stock and service results to help characterize the electrification scenarios, which are developed primarily using an accounting framework (Section 5). As mentioned above, a range of factors—both economic and non-economic in nature—could challenge (or support) the widespread adoption of efficient electric buildings technologies, including challenges and opportunities associated with existing building retrofits, requirements for new (supporting) infrastructure, familiarity, consumer preferences, and public acceptance. Here, we provide additional discussion related to these considerations that are not fully captured in the modeling.

Electrification of existing buildings can require changes in the mode of end-use service delivery as well as supporting infrastructure, which can substantially impact (increase) the cost of retrofit and can reduce the installer or customers willingness to adopt, even in the case when the cost is not substantially impacted. Consider, for example, heat pump retrofits. Most heat pumps on the market today deliver heat via forced hot air—either directly into a room or through ducting. Retrofitting buildings that use hot-water or electric resistance baseboard radiators require the installation of ducting or, alternatively, the reliance on ductless heat pumps (also referred to as mini-splits), which could subsequently require the need for multiple units, depending on the size and configuration of the building. As a result, building or homeowners with incumbent hot-water or resistance-based heating, may be less likely to adopt heat pumps than those with ducting in place. Furthermore, substantial increases in buildings electricity demand from electrification (including PEVs) could impose additional electrical supply infrastructure (or service) upgrades to meet the increased demands.

Despite these potential barriers, heat pumps also offer a benefit over incumbent heating appliances—they provide both heating and cooling services, and, in the case of integrated heat pumps, they provide space heating, space cooling, and water heating services. The multi-service value of ASHPs can help lower effective costs.[60]

Finally, even in the absence of cost challenges, cultural acceptance or familiarity can have substantial impacts on adoption. For example, the challenges of achieving high penetrations of advanced electric cooking appliances are perhaps less steep physically, or even economically driven, than they are for ASHPs. Induction cooktops are more energy efficient and offer greater temperature control than electric resistance or natural gas cooking, but the latter is widely preferred by most professional and many home cooks, and therefore continues to dominate the market in high-end residential and commercial kitchens. Widespread adoption of induction cooktops and other advanced appliances would likely require shifts in consumer preferences when the perceived or actual benefits of the new technologies outweigh those of the incumbent technologies.

Although the EP modeling does not explicitly capture this full suite of tradeoffs, the Medium and High scenarios assume the balance of these tradeoffs contributes to the different levels of adoption of electric technologies specified. A detailed evaluation of the costs, barriers, and benefits of all technologies would likely require case-by-case study. Although our analysis does not include such an evaluation, in the above, we highlight some important factors. Our analysis

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[60] See Jadun et al. (2017) for levelized cost comparisons of ASHPs providing just heating compared to heating and cooling.

also shows scenarios in which many of the challenges to buildings electrification are overcome and electricity becomes the predominant fuel for all major buildings end uses. In fact, in the High scenario, electricity comprises over 62% and 75% of 2050 final energy consumption in residential and commercial buildings, respectively, compared with 45% (residential) and 62% (commercial) in the Reference scenario and 43% (residential) and 61% (commercial) in recent years.[61]

6.3 Industry

Like residential and commercial buildings, demand drivers for the industrial sector are based on assumptions from the AEO2017 Reference case (EIA 2017c). Unlike buildings, however, most industrial service demands rely heavily on combustion fuels in the Reference and electrification scenarios. We assume industrial end uses experience many barriers to electrification that are generally associated with maintaining profitability and avoiding disruption to production processes. We developed our industrial adoption heuristic (Appendix D) based on a relative ranking of typical productivity benefits provided by industrial electrotechnologies. Our choice to view industrial electrification through the lens of productivity benefits may result in conservative adoption assumptions for certain electrotechnologies, even in the High scenario.

Boiler use represents a significant industrial energy end use, but electric boilers are adopted only in the High scenario, based on our assumptions of their limited productivity benefits relative to other industrial electrotechnologies. Likewise, industrial space heating is another end use served by electrotechnologies that offer limited benefits for increasing productivity. The Medium and High scenarios, however, show electrification due to adoption assumptions shared with commercial buildings space heating. By 2050, we assume heat pumps constitute 24% and 60% of industrial space heating service demand in the Medium and High scenarios, respectively—up from roughly 9% in the Reference scenario.

We assume the other large electrification impacts occur in several process heating service demands, including curing, drying, and other industrial process heating. Under our adoption heuristic, we assume process heating electrotechnologies—such as infrared (IR) and ultraviolet (UV) heating, and induction melting—provide benefits, such as improved process control, production rate, or product quality, which increase their adoption in the Medium and High scenarios. Figure 6.6 shows the electrification of industrial curing and drying increase from 0% in the Reference scenario to 63% for industrial curing and 32% for industrial drying in 2050 under the High scenario. Electricity comprises about 15% and 8% for 2050 curing and drying, respectively, in the Medium scenario. We assume new adoption of industrial heat pumps and induction furnaces, as well as increased adoption of resistance heating technologies increase electricity's share of other process heating to nearly 30% and 56% in the Medium and High scenarios, respectively. We note that for the Reference scenario, we assumed electricity used to meet industrial process heat service demands is electric resistance-based heating and melting. Induction melting, industrial heat pumps, and other electrotechnologies likely constitute portions of this service demand, but data at sufficient detail to identify individual technologies in the Reference scenario are lacking.

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[61] Based on estimates from EIA 2009 Residential Energy Consumption Survey (RECS 2009) and EIA 2012 Commercial Buildings Energy Consumption Survey (CBECS 2012).

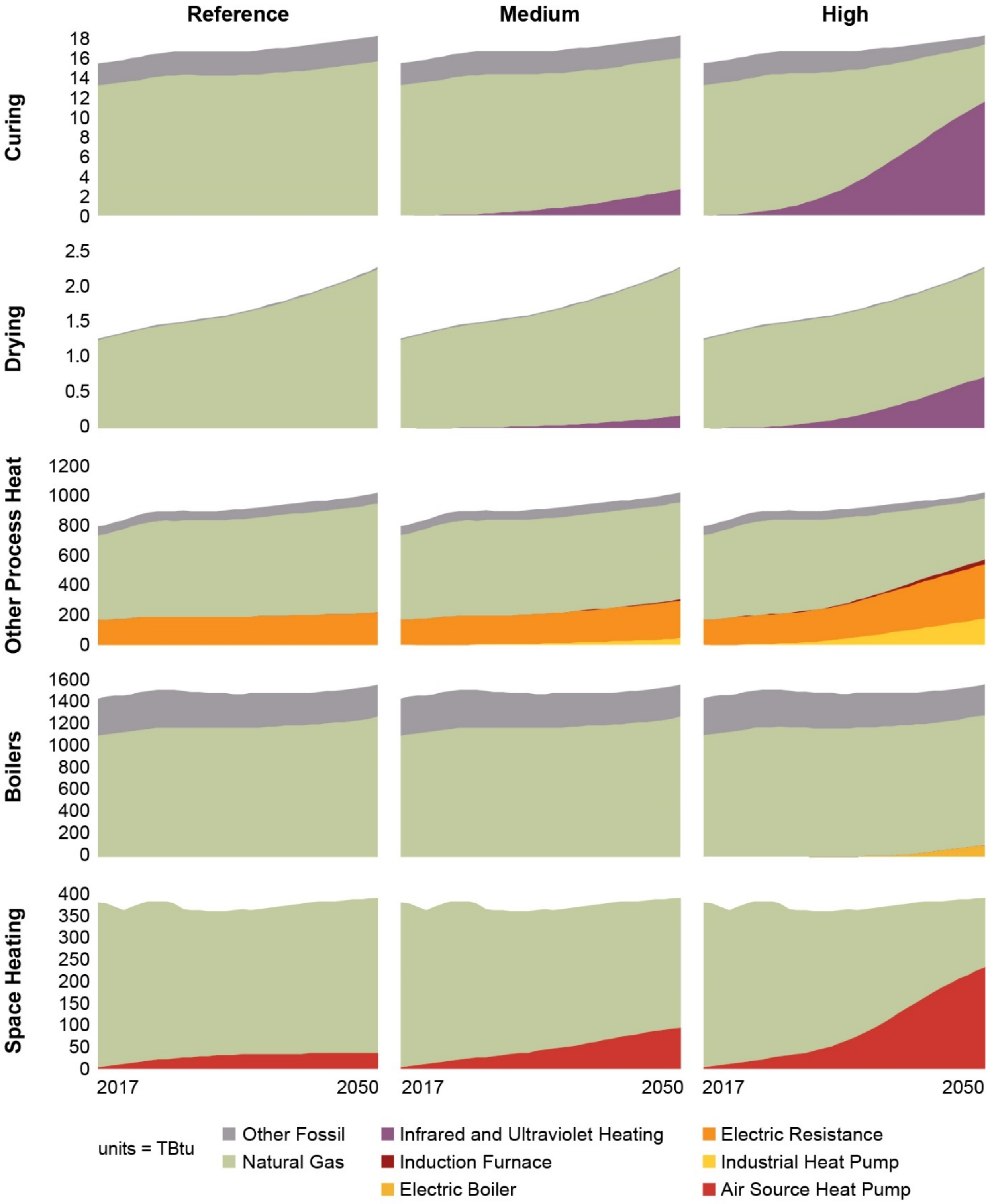

Figure 6.6. Industrial service demand by fuel type in the electrification scenarios

EP models several technologies for each end-use service. These technologies are grouped into categories in the figure for convenience.

Although significant advancements have been made to the industrial sector's representation of EP to support the present analysis (Section 5), detailed techno-economic modeling of the entire sector—as well as data to inform such modeling—remains a key research need. Moreover, the evolution of the U.S. industrial sector can be much more sensitive to hard-to-predict structural and macroeconomic factors in the future U.S. and global economies. As a result, forecasting or assessing potential transitions in industry is fraught with challenges and uncertainties. In the remainder of this section, we supplement our modeling analysis with additional considerations for industrial electrotechnology adoption.

An industrial firm's decision whether to adopt an electrotechnology likely competes with other capital equipment investment decisions, and firms may encounter similar institutional and financing barriers as observed by Anderson and Newell (2004) for purchases of energy efficiency equipment. The cost of power supplies required by certain electrotechnologies may result in installed costs that are triple the equivalent combustion-fired equipment (EPRI Center for Materials Fabrication 1993). Despite their potentially higher installation costs, many electrotechnologies are more energy efficient; however, energy often represents a small portion of total input costs for manufacturing. Energy costs for all manufacturing industries constituted 19% of the total costs of all factors of production (i.e., labor, capital, and intermediate inputs of materials, services, and energy) in 2010 (Jorgenson, Ho, and Samuels 2012). The range included 1.4% for transportation equipment manufacturing and 93% for coke, refined petroleum, and nuclear fuel manufacturing. This large range highlights the heterogeneity in the sector, which contributes to the difficulties of modeling and analyzing industrial electrification.

Due to potential investment barriers, electrotechnologies that increase productivity by improving product quality, increasing process throughput, or providing other benefits that increase profit are much more appealing to industrial firms. For example, certain electrotechnologies can provide more precision and control and can more quickly reach required temperatures, which may increase production throughput relative to incumbent combustion technologies. Lower scrap rates and scale formation, as well as reduced labor requirements are associated with induction furnaces (Cheremisinoff 1996). The extent to which these productivity benefits of industrial electrotechnologies are achieved can have a significant impact on their desirability. If these attributes are not first identified and quantified, and then recognized and incorporated into capital investment processes, the economic case for many industrial electrotechnologies will likely remain a challenge.

The long lives of industrial equipment also act as a barrier to widespread electrification in the industrial sector. Conversely, however, there is evidence that overall economic conditions, not equipment age, may drive capital investment decisions (Worrell and Biermans 2005; Doms and Dunne 1998). And, industrial facilities may also be retrofitted at more frequent intervals than with equipment replacement (Wesseling et al. 2017). These complexities can further complicate efforts to model industrial equipment stock turnover.[62]

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[62] Because of these complexities, we assume different industrial equipment lifetimes in our scenarios. This contrasts with representations of buildings and transportation equipment, where equipment lifetimes are the same in all scenarios. Specifically, we assume the lifetimes of all industrial equipment, except for HVAC equipment for industrial buildings, are reduced by 50% in the High electrification compared with the Medium and Reference scenarios.

Several energy-intensive industries that we did not consider for additional adoption of electrotechnologies in our scenarios face large technological hurdles for electrification. For example, plasma furnaces and other types of electric kilns can produce the high temperatures (>1,400° C) needed for sintering clinker in cement production. These electrotechnologies, however, may be unavailable at the required production scale (Philibert 2017). Existing petrochemical manufacturing processes such as naphtha steam cracking are not suitable for direct electrification due to their tightly integrated nature and reliance on byproducts as combustion fuels (Lechtenböhmer et al. 2016; McMillan et al. 2016). However, commodity petrochemicals such as ethylene can be produced by electrochemically reducing carbon dioxide, but they are not currently at the required industrial scale (Schiffer and Manthiram 2017). Continued advancements in electric technologies that overcome some of the hurdles identified in these examples are likely needed to expand electrification to these energy-intensive industries.

7 Results: Electricity Consumption

The adoption of electric end-use equipment and the transition from non-electric to electric technologies, along with their performance characteristics, impact the amount and shape of power consumption. In this section we characterize these estimated changes in demand for the electrification scenarios. Future EFS reports will provide additional geographic and technological resolution on electricity consumption as well as analysis of future electricity production.

7.1 Annual Electricity Consumption

The top row in Figure 7.1 shows annual electricity consumption by economic sector in the three electrification scenarios (using Moderate technology advancement assumptions).[63] In the Reference scenario, annual electricity demand grows with a CAGR of 0.65% from 2016 to 2050. This represents an increase of about 25% over that period and reaching 4,722 TWh in 2050.[64] Electricity demand growth in our Reference scenario is similar to growth in the AEO2017 Reference case, which is to be expected as structural assumptions, demand drivers (e.g., population and economic growth) and technology adoption are largely based on the AEO2017. As discussed in Section 4, we assume relatively limited adoption of many electric technologies in our Reference case, therefore future increases in electricity consumption in the Reference result primarily from overall service demand growth, particularly in the buildings and industrial sectors, which are driven by a growing population and economy.[65] Transportation electricity use remains limited relative to the other sectors in the Reference scenario.

As a result of this limited spread of electrification in the Reference case, we find a narrow range in electricity consumption (Figure 7.2) across all electric technology advancement projections, where the range is driven by the variations in end-use technology efficiencies assumed across the Slow, Moderate, and Rapid technology advancement projections (Jadun et al. 2017). These projections only include variations in buildings and transportation technology advancements. Text Box 7.1 presents results from technology sensitivity scenarios with performance improvements in industry.

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[63] Consumption includes electricity used by all end-use devices and differs from electricity *sales*, which might be lower due to distributed (on-site) electricity production. We represent combined heat and power and distributed rooftop photovoltaics in our electricity “supply” analysis to be presented in future EFS reports. Electricity consumption from the extraction, processing, and transport of fossil fuels is tracked on the supply-side and is dependent on the demands for each fuel. The figure notes in this section clarify the scope of the reported energy and electricity values, including whether the figures consider fossil fuel extraction and refining.

[64] These percentage increases are based on our modeled 2016 total of 3,783 TWh, which differs from the historical value of 3,889 TWh (Figure 2.1) due to small modeling errors (representing <3%) primarily in the industrial sector.

[65] In all scenarios, we assume—based on AEO2017 Reference case projections—population, building square footage, and VMT in 2050 are 22%, 36%, and 29%, respectively, over 2016 values.

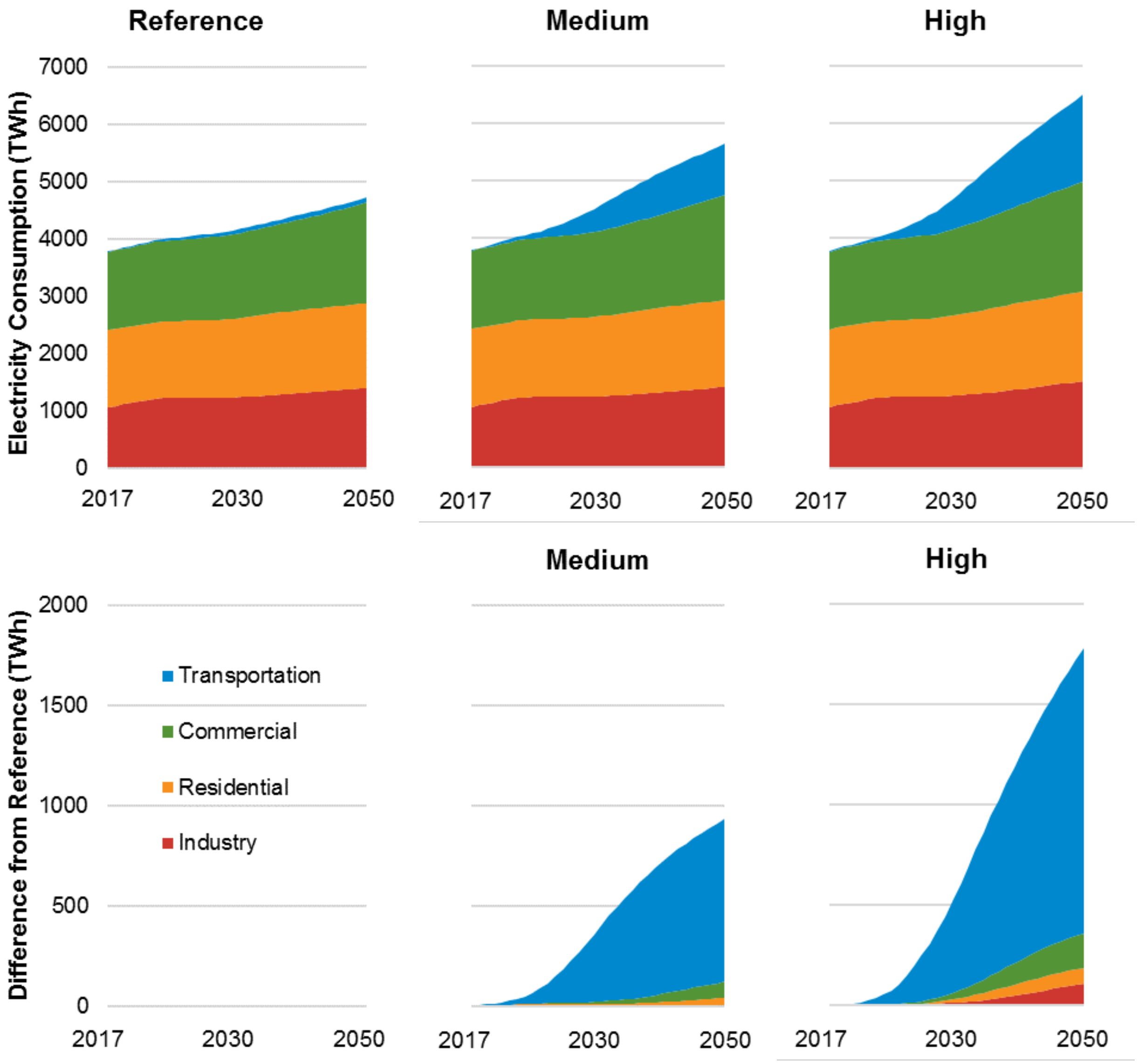

Figure 7.1. Annual U.S. electricity consumption (top) and difference from Reference (bottom)

Moderate technology advancement projections are shown.

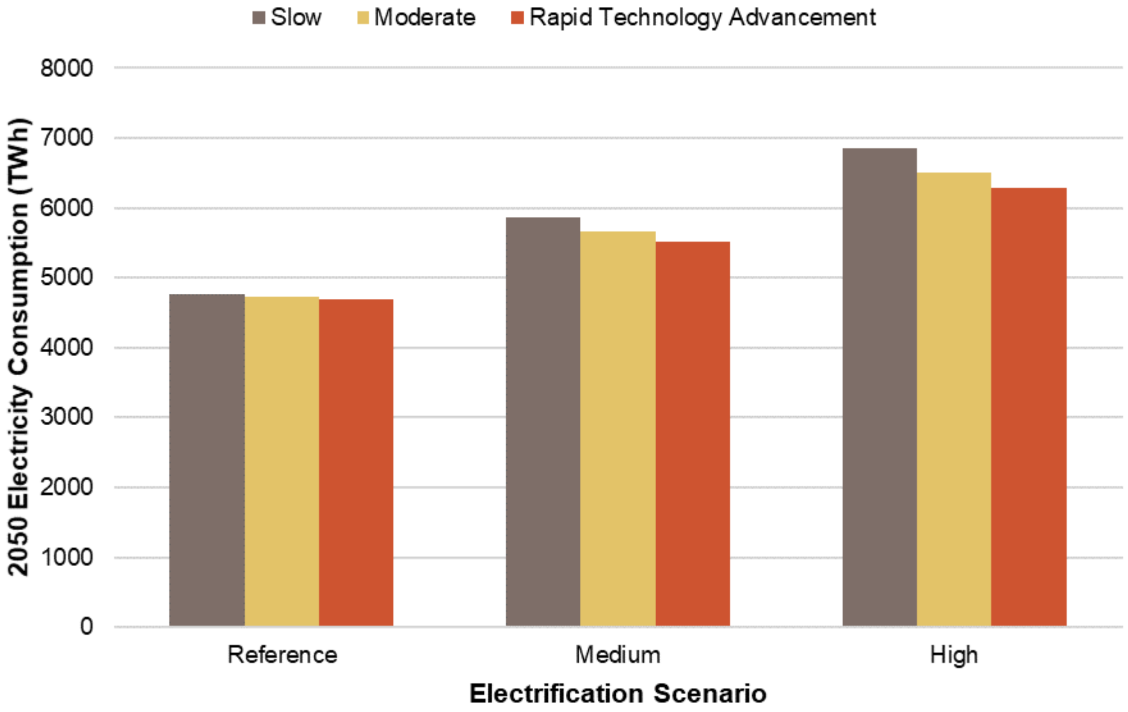

Figure 7.2. Electricity consumption in 2050 by technology adoption and advancement scenario

The adoption of electric technologies in the Medium and High scenarios results in much greater electricity consumption growth than in the Reference scenario. In the Medium scenario, annual electricity demand grows by 1.2%/year[66] and reaches 5,656 TWh by 2050 with Moderate technology advancements. Electricity consumption in 2050 spans a wider range—5,520 TWh (1.1%/yr from 2016 to 2050) to 5,871 TWh (1.3%/yr)—when the full set of technology advancement projections is considered. This range reflects possible efficiency improvements that could impact the degree to which electricity consumption grows with the adoption of end-use electric technologies. In other words, Figure 7.2 shows how more efficient end-use technologies, such as PEVs with high effective miles per gallon or heat pumps with high coefficients of performance, could mitigate some of the growth in annual electricity consumption despite their widespread adoption in the scenarios. In contrast, without technology advancements that improve efficiency, electrification would yield noticeably higher electricity demand.

With Moderate technology advancements (Figure 7.1), we estimate an increase of about 934 TWh in 2050 consumption in the Medium scenario relative to the Reference scenario. Most (87%) of this incremental growth is from transport electrification as assumed in the Medium scenario. Increases in 2050 electricity consumption in other sectors are more modest, including 123 TWh for residential and commercial buildings combined relative to the Reference scenario. Despite the increased adoption of industrial electrotechnologies in the Medium scenario, we find nearly identical industrial electricity consumption between the Reference and Medium scenarios in all years. The reason for this offsetting behavior is that industrial electricity consumption includes uses of electricity for fossil fuel extraction and refining, which is tied to the amount of

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[66] Unless otherwise noted, all reported annual rates are compound annual growth rates from 2016 to 2050.

fossil fuel demand from *all* sectors. Electrification, particularly PEV adoption, reduces domestic consumption for fossil fuels (see Section 7.2) and thus impacts industrial electricity use. In the Medium scenario, these reductions nearly perfectly, and coincidentally, offset the incremental demand for electricity due to industrial electrification.[67] We note that this assumption does not consider possible increases in fossil fuel exports and similar effects, which could reduce or eliminate this offsetting behavior.

In the High scenario, more widespread transport electrification, including adoption of electric long-haul medium- and heavy-duty trucks, leads to an increase of over 1,424 TWh in transportation-related electricity consumption relative to the 2050 Reference scenario. Incremental electricity consumption in buildings is estimated to be over 247 TWh by 2050 (split 69% and 31% between the commercial and residential sectors). Meanwhile, industrial electrification increases electricity demand by an additional 112 TWh in 2050.[68] Altogether electricity demand in the High scenario is estimated to grow by 1.6%/yr with the Moderate technology advancement and 1.5%/yr–1.8%/yr across all technology advancements. Annual electricity consumption in the High scenario is estimated to reach 6,846 TWh, 6,505 TWh, and 6,280 TWh with Slow, Moderate, and Rapid technology advancements, respectively.

Electrification of transportation clearly has an outsized role on annual electricity consumption compared to electrification in other sectors in the modeled scenarios. One reason for this is that electrification in transportation has greater potential than other sectors on an energy consumption basis (see Figure 1.1). For example, in 2016 electricity comprised about 0.1% of final energy consumption in transportation compared with 45%–53% in the two buildings sectors and about 15% in industry. For the buildings sectors, where electrification has historically been the greatest among all sectors, future electrification would have the biggest impact in a small number of high energy-consuming end uses, including space heating, water heating, and cooking. Another reason the incremental annual electricity consumption in buildings is less than that of transport is the very high-performance efficiency of ASHPs used for space heating. In certain sectors (e.g., residential water heating), total electricity consumption declines in the High electrification scenario due to the replacement of electric resistance technologies. Although most electric technologies use less energy to produce the same service as their non-electric counterparts, ASHPs are particularly efficient and have great potential for even further improvements (Jadun et al. 2017). As one of the leading technologies used for buildings electrification, ASHPs yield a relatively modest amount of incremental buildings-related electricity consumption despite the great deal of space heating services provided in our Medium and High scenarios. For industry, the more-modest electrification in our scenarios is driven in large part by the omission of certain key industrial activities identified by Table 1.1.

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[67] For example, electrification in the Medium scenario leads a 33 TWh increase in 2050 industrial electricity consumption for process heating, drying, curing, and other demands, but a 32 TWh reduction in electricity use for fossil fuel extraction and refining relative to the Reference.

[68] This is on net, including reductions in electricity consumption from fossil fuel refining and extracting.

Despite the larger share of transport-driven *annual* electricity consumption shown in Figure 7.1, electrification in the other sectors can have an outsized impact on electricity load shapes as we discuss below. We also note that the impact of future technology development on electrification-driven incremental electricity consumption can differ between sectors. For example, in the High scenario we find a total difference of 566 TWh in 2050 annual electricity consumption between the Slow and Rapid technology advancement projections (Figure 7.2), but over 29% of this difference is from the buildings sector (primarily variations in future heat pump efficiencies) despite the smaller effect of buildings electrification, compared with transportation, on incremental annual electricity consumption (Figure 7.1).

Electrification-driven growth in electricity consumption in the High scenario is certainly greater than the growth projected in the Reference scenario or the growth experienced over the past decade. However, when taking the longer historical view, the growth rate found in the High scenario through 2050 (1.5%/yr–1.8%/yr) is similar to or even significantly lower than that observed in other historical periods (Figure 2.1). For example, from 1950 to 2016, the average CAGR was about 4% per year. The range in CAGRs projected in the High Scenario over the future 34 years is, in fact, similar to the rate (1.8%/yr) found during the prior 34 years (1982–2016).

Although the projected national electricity consumption CAGRs experienced in the scenarios fall below long-term historical rates, absolute and non-compounding year-to-year changes in consumption driven by electrification can be unprecedented. For example, in the High scenario, the average increase in annual electricity consumption from 2016 to 2050 is about 80 TWh/yr. In comparison, the average absolute annual growth rates over the past 34 years and from 1950 to 2016 are significantly lower (50–55 TWh/yr). In the Medium scenario, the average year-to-year change in consumption (during 2016–2050) is similar to these historical averages (55 TWh/yr). Significant year-to-year variance is observed in the historical data, including 185 TWh for the largest absolute annual increase and 141 TWh for the largest *decrease*, due to a wide range of factors that are not modeled in our analysis.[69] The long-term averages wash out many of these factors and show how sustained growth at levels consistent with the High scenario has not been observed historically. For example, in the High scenario, decade-averaged growth peaks around 110 TWh/yr during the 2040s compared with a historical (10-year average) peak of less than 90 TWh/yr during the early 1970s and mid-1990s. This unprecedented absolute growth in annual electricity consumption can significantly alter supply-side infrastructure development requirements even as the CAGRs fall below historical observations.

In addition to these comparisons, the electrification scenarios from our analysis could also be put in context with demand growth scenarios generated by others. Text Box 7.2 compares 2050 electricity consumption from the three core electrification scenarios with those from the recent literature.

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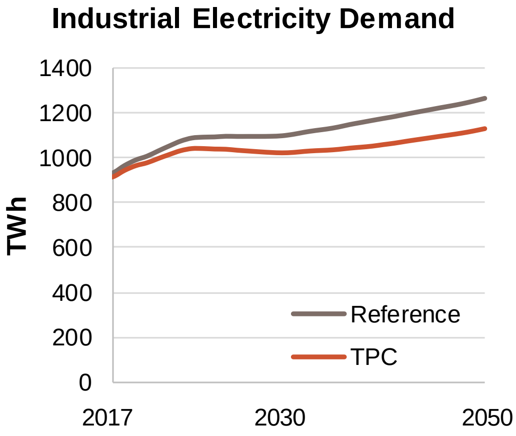
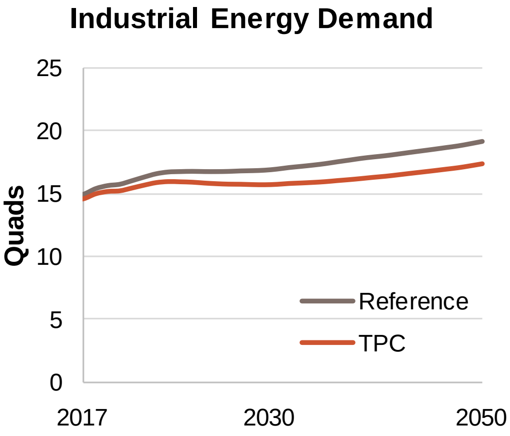
[69] For example, the largest decrease occured between 2008 and 2009, and it is likely caused by decreases in economic activity during the Great Recession.

Text Box 7.1. Impacts of Industrial Performance Improvements on Electricity Demand

As described in Section 4, we model future electricity consumption scenarios with variations along two primary dimensions for electric end-use technologies: adoption and advancement. Along the adoption dimension, we include electrification in all sectors, including buildings, transportation, and industry. For the advancement dimension, however, we only model variations in select buildings and transportation technologies, based on projections from Jadun et al. (2017), but we do not vary assumptions about industrial technologies or processes. The primary reason industrial technology advancement ranges are omitted is the complexity and heterogeneity of industrial processes and equipment. These factors make it challenging to develop trajectories of technology innovation and implement the trajectories in our modeling framework.

In this text box, we present sensitivity scenarios to quantify the extent to which efficiency improvements in industry might change energy and electricity consumption. We model projected efficiency improvements based on the technical possibility curves (TPCs) used by NEMS. TPCs define the annual change in energy intensity of existing and new capacity and technology bundles relative to a 2010 baseline. TPCs are derived from assumptions about changes to energy intensity and new technology adoption over time, including efficiency improvements to buildings and transportation equipment for non-manufacturing industries. They do not, however, provide technology-level detail. The figures show how industrial energy and electricity consumption are estimated to be lower with the TPC efficiency improvements relative to our Reference scenario. (The figures exclude energy and electricity use for fossil fuel extraction and refining.) For example, the TPC scenario results in 9% lower energy consumption and 11% lower electricity consumption in the industrial sector in 2050. Although our primary scenario analysis does not include a range of industrial technology advancements, these results suggest that improving efficiency in industry could yield measurable energy and electricity savings, and, presumably, system and producer cost savings as well.


Industrial Electricity Demand


Industrial Energy Demand

Text Box 7.2. A Literature Comparison of 2050 Scenarios

To help contextualize the EFS scenarios, we compare projected 2050 electricity consumption in our three core scenarios with other recent studies. We compare our scenarios with the range of electricity demand in 2050 from AEO2017 (several scenarios) and six studies that considered electrification within a suite of different strategies, mostly in the context of transformation pathways to reduce greenhouse gas emissions: EPRI (2018), Williams et al. (2015), The White House (2016), Weiss et al. (2017), Iyer et al. (2017), and Steinberg et al. (2017). This recent literature reveals a very broad range of possible electricity demand growth in the future and the figure below shows how the EFS scenarios fit within this range. For the EFS scenarios, the ranges represent all technology advancements modeled while the markers show the results for the Moderate technology projections only. By design, the EFS Reference scenario is aligned with the AEO2017 results and falls below or on the low end of the ranges from the other studies. Consumption estimates from the Medium and High scenarios fall within the aggregate, and very broad, range from the other six studies.

Variations in 2050 electricity consumption from this literature collection reflects the diverse drivers and technologies envisioned in those studies. For example, the highest estimates are from Steinberg et al. (2017) and Weiss et al. (2017), as these studies focus primarily on electrification potentials and, in the case of Steinberg et al. (2017), assumes significant electrolysis-based hydrogen production that leads to significant demand for electricity. In contrast, Iyer et al. (2017), The White House (2016), and Williams et al. (2015) examine decarbonization pathways that rely on diverse energy transitions, including electrification, energy efficiency, and bioenergy. EPRI (2018) focuses on electrification, but where adoption is economically driven under a range of market conditions. Electricity consumption in the EFS Medium scenario falls toward the high end of EPRI's scenarios suggesting that the qualitative adoption projections in EFS are loosely consistent with favorable economic conditions for electrification identified by EPRI. The High scenario is more consistent with electrification estimates under deep decarbonization scenarios—but remains below technical potential for electrification. Additional differences in electrification and electricity consumption within each sector exist between the EFS and prior studies. For example, even greater building heating electrification in cold climates is sometimes assumed in some prior studies and significant variations in industrial electrification exist across all studies. Overall, the collection of studies suggest that electrification can have a significant impact on future demand growth.

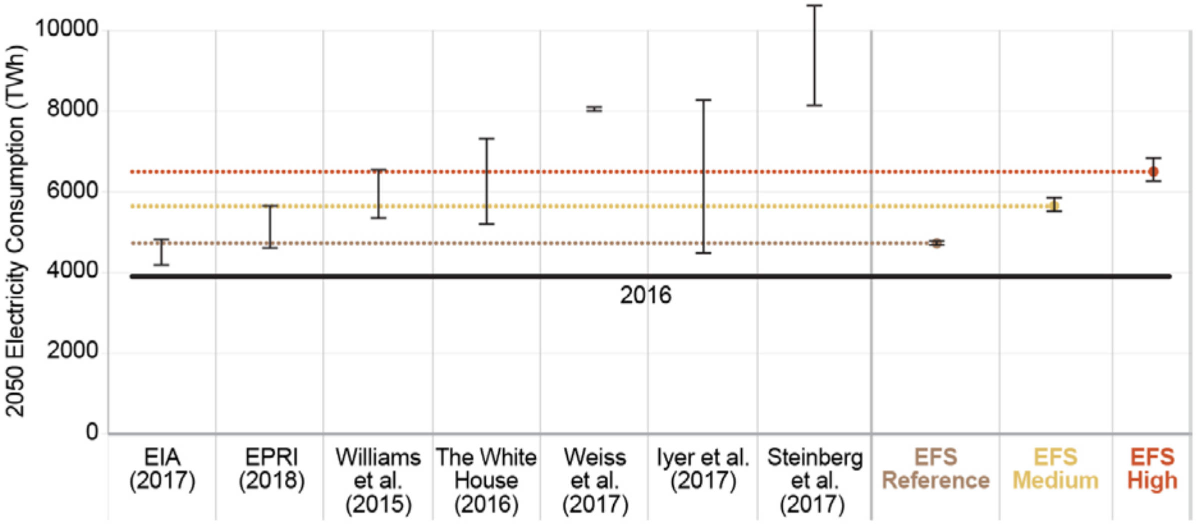


Figure 7.3 shows another measure of the degree of electrification in our adoption scenarios: electricity's share of final energy consumption in the scenarios (all using Moderate technology advancement assumptions). The figure shows how the use of electricity increases at a greater rate than uses of other fuels in the Medium and High scenarios in all sectors, such that electricity comprises 32% and 41% of total site energy use in 2050, compared with 23% in the Reference scenario in 2050 and 19% in 2016. For all sectors, trends in electricity shares under the Reference scenario largely follow those from the historical data (Figure 2.2);[70] continued growth in electricity use is largely restricted to the buildings sectors, projected relative electricity use is found to be flat over time in industry, and although an increase in transportation electricity share is observable, the magnitude of electricity use in transportation remains small (at about 1% in 2050). In contrast, greater reliance on electricity is found in all sectors for the Medium and High scenarios, including 29% in transportation under the High scenario with consistent growth in industry and an acceleration toward majority-electric in buildings for both scenarios.

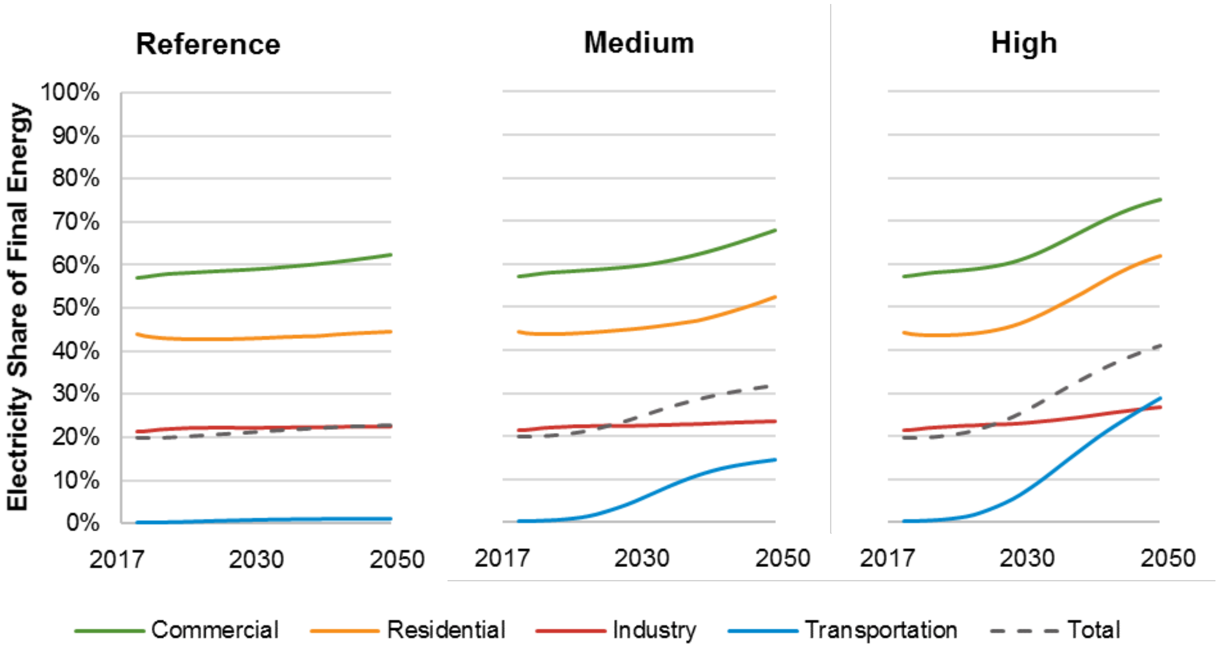


Figure 7.3. Electricity share of final energy consumption

Moderate technology advancement projections are shown. The estimates exclude energy and electricity used for fossil fuel extraction and refining, which would slightly lower the electricity shares for industry and in total.

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[70] The actual historical data (Figure 2.2) and the modeled data (Figure 7.3) do not match perfectly even for historical years (2015–2017); however, differences are slight and within a few percentage points for each sector and in total.

The metric presented in Figure 7.3 understates the amount of electrification in the scenarios, as the energy-based perspective does not fully reflect how electric technologies often provide a greater amount of service per unit of energy. In other words, although the High scenario results in 41% electricity share of total final energy in 2050, the service share from electric technologies is much higher for many end uses because electric technologies typically have greater energy efficiency than their non-electric counterparts. Different services in different sectors are not directly comparable; therefore, aggregating service shares to estimate a total service share from electricity is not possible. Nonetheless, Section 6 presents the fraction of services provided by electricity-based technologies for several end uses. These examples show how electricity provides a significant or large majority of services in many cases under the High scenario by 2050. Examples are that electric VMTs comprise over 79% of total VMTs for LDVs (Figure 6.3), electric devices provide over 58% space heating services in both commercial and residential buildings (Figure 6.5), and 63% of curing services rely on industrial electrotechnologies (Figure 6.6).

Table 7.1 summarizes the 2050 electricity consumption and shares, by sector and in total, for all nine electrification and technology advancement scenarios. Recent historical (2016) values are also provided for context. Of the four sectors, energy use in industry changes the least between each scenario. Viewing industry in aggregate, however, hides the extent of subsector variation in electrification. For example, the electricity share of curing energy increases from 0% to nearly 63% by 2050 in the High scenario, which drives electrification in industries where we have characterized curing processes. Similarly, electrification of other types of processes that fall under the process heating end-use category (mainly melting and heating processes for metals) nearly triples by 2050 in the High scenario. This change mostly notably affects transportation equipment manufacturing, as well as the category of other, miscellaneous manufacturing.

Table 7.1. Electricity Consumption and Share of Final Energy by Sector and Scenario

Annual Electricity Consumption (TWh)		**2050 Reference**			**2050 Medium**			**2050 High**		
	2016	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**
Transport	7.5	78	88	101	809	898	1,019	1,365	1,512	1,712
Residential	1,418	1,462	1,474	1,503	1,481	1,518	1,589	1,491	1,551	1,657
Commercial	1,379	1,751	1,755	1,762	1,824	1,835	1,855	1,909	1,925	1,956
Industrial	1,084	1,405	1,405	1,406	1,405	1,406	1,408	1,515	1,517	1,520
Total	**3,889**	**4,696**	**4,722**	**4,772**	**5,520**	**5,656**	**5,871**	**6,280**	**6,505**	**6,846**

Percent (%) of Final Energy		**2050 Reference**			**2050 Medium**			**2050 High**		
	2016	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**
Transport	0	1	1	1	13	14	16	27	29	31
Residential	45	44	45	45	52	52	53	61	62	63
Commercial	53	62	62	62	68	68	68	75	75	75
Industrial (excluding refining)	15	23	23	23	23	23	23	27	27	27
Total	**19**	**23**	**23**	**23**	**31**	**32**	**33**	**40**	**41**	**42**

See notes for Figures 2.1 and 2.2 for data sources for the historical (2016) data. Attribution to each sector is based directly on EIA, which may include behind-the-meter PEV charging in the residential and commercial sectors. Historical 2016 data presented here differ slightly from modeled 2016 values from EP. Data also include net self-generation of electricity from renewable sources (except geothermal) and combustible fuels. The consumption data include EIA estimates of behind-the-meter solar generation based on estimated growth rates from the AEO. The electricity consumption estimates include electricity used for fossil fuel extraction and refining; however, estimated final energy shares from electricity do not include these uses.

Figures 7.1–7.3 and Table 7.1 present national electricity demand results, but electrification-driven consumption is not distributed uniformly across all U.S. regions, given the differences in how electricity is used. Figure 7.4 shows how incremental electricity consumption—on absolute and relative terms—varies by state in the High scenario, relative to the Reference. Electricity consumption in the High scenario is estimated to increase by over 50% in several states, compared to 38% nationally.[71] In some states, electrification in the High scenario increases 2050 demand by only about 20%. These differences reflect a wide range of variations in equipment vintage, service demand growth, policies, and other conditions experienced historically and modeled in the AEO2017 Reference case as well as in EP. However, the nature of electrification can also drive some of these differences. For example, Figure 7.4 shows how incremental electricity consumption from the buildings sector is greater in states with cold climates due to both the lower efficiency of ASHPs in cold temperatures and greater heating service demands per household in cold climates. Ultimately, while this report characterizes national adoption, consumption, and trends, a better understanding of local drivers and barriers behind electrification will be needed to inform local decisions related to electrification or to assess the local impacts of electrification. Regional and state-level data from the EFS scenarios can be found on the project website (www.nrel.gov/efs) and can be explored to provide additional insights.

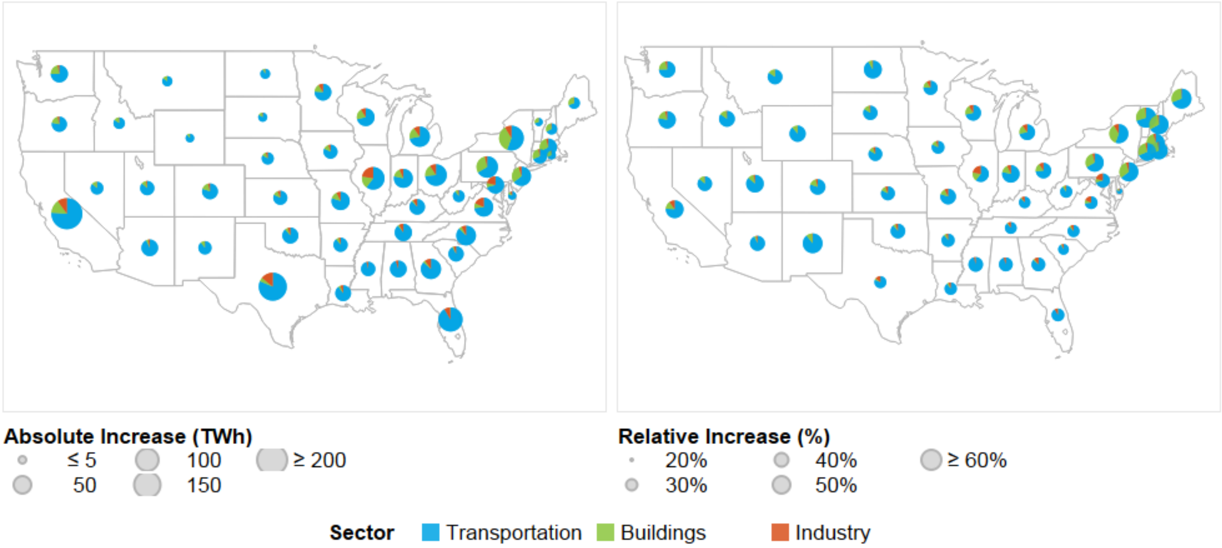

Figure 7.4. Incremental 2050 electricity consumption in the High scenario, relative to the Reference, in absolute (left) and relative (right) terms

Moderate technology advancement projections are shown. The percentages shown are based on total (from all sectors) 2050 consumption in the Reference. The estimates exclude electricity consumption from fossil fuel extraction and refining.

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[71] National electricity consumption in 2050 is 20% higher in the Medium scenario than in the Reference scenario. All reported values are for the Moderate technology advancement cases.

7.2 Avoided Non-Electric Fuel Consumption

As previously mentioned, the greater use of electricity displaces some direct fuel use for end-use services.[72] Figure 7.5 shows the differences in gasoline, diesel, and natural gas consumption (at the site) for the three core electrification scenarios.[73] These fuels represent the ones displaced to the greatest extent in the Medium and High electrification scenarios, relative to the Reference scenario.[74] In the Medium scenario, gasoline use in 2050 is reduced by 52% (8 quads) relative to the Reference scenario primarily because of the modeled adoption of electric LDVs. Reductions in use of diesel and natural gas in 2050 are more modest at 15% (1.4 quads) and 16% (2.2 quads), respectively. In contrast, in the High scenario, significant reductions in all three fossil fuels are found relative to the Reference scenario: 74% (12 quads) for gasoline, 35% (3.4 quads) for diesel, and 37% (5.3 quads) for natural gas. Greater reductions in site use of multiple fossil fuels in the High scenario stem from greater amounts of electrification occurring in a wider set of end uses and regions. Electrification of long-distance medium- and heavy-duty transportation reduces reliance on diesel. Electricity use in buildings technologies displace natural gas consumption (most notably for space heating, water heating, and cooking). Greater reliance on industrial electrotechnologies replaces a range of fossil fuels.

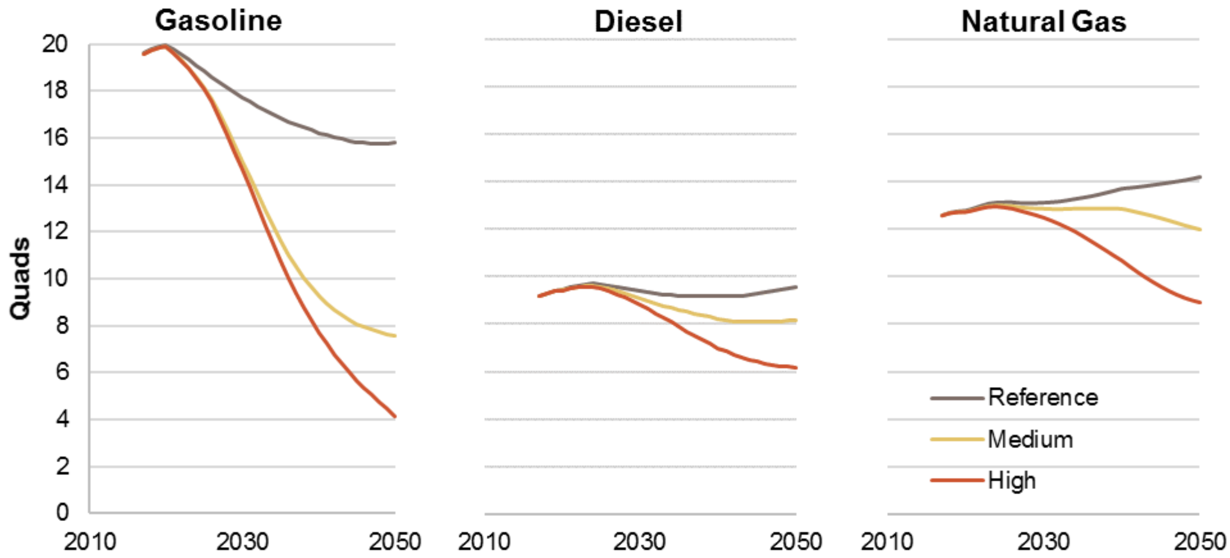

Figure 7.5. Site fossil fuel use by scenario

Moderate technology advancement projections are shown. Fuel use for electric power generation is not included in the values shown. Estimates also exclude fuel consumption for fossil fuel extraction and refining.

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[72] Non-fuel (i.e., feedstock) energy uses are outside our analysis boundaries and are not avoided in the electrification scenarios as a result. Non-fuel energy use in manufacturing industries constituted approximately 5.3 quads in 2014 (MECS 2017).

[73] All scenarios include policies and regulations as of 2017. This include would impact the absolute and relative amount of fuels consumed in the scenarios. For example, the reduction in gasoline consumption over time estimated for the Reference scenario is driven by assumed improvements in vehicle efficiency, which are impacted by policies and regulations. However, our analysis is not intended to isolate the impacts of these policies.

[74] This is in absolute terms. Other avoided fuels in the higher electrification scenarios include fuel oil, liquefied petroleum gas, and coal.

Figure 7.5 includes only U.S. domestic fuel consumption at the site or directly by vehicles, as the focus of this report is on the demand-side. Although electrification can reduce on-site fossil fuel use, it will increase the amount of upstream energy consumption (e.g., to produce electricity). As a result, Figure 7.5 and the analysis in this report presents an incomplete picture of overall fuel use, with the largest gap for natural gas being due to the current and anticipated reliance on natural gas for power production (see Figure 2.1). For example, EPRI (2018) shows how total natural gas consumption can increase or remain stable even with high levels of electrification and under a range of carbon price futures, if natural gas prices remain low. In addition to potential increases to indirect domestic uses of fossil fuels (e.g., through power production), reductions in on-site fuel use from electrification could also result in expanded export markets. For the EFS scenarios, supply-side and overall fuel use will be presented in future EFS reports.

Although our demand-side analysis cannot provide a complete picture of fuel consumption, it does allow for an assessment of changes in *final* energy consumption, which is a relevant measure, as many advanced electric technologies have greater energy efficiency than their non-electric counterparts. For example, both electric vehicles and heat pumps are typically three to four times more efficient in converting energy into their respective services provided (power at the wheels and warming interior spaces) than conventional internal combustion engine vehicles and natural gas boilers, respectively (Jadun et al. 2017).

Figure 7.6 shows how final energy consumption declines across all sectors and the energy system as a whole through electrification.[75] In the Reference scenario, final energy consumption remains roughly flat and is estimated to total 68 quads by 2050. In comparison, final energy consumption in 2050 is 13% and 21% lower (relative to the Reference) under the Medium (to 59 quads by 2050) and High (53 quads) scenarios. As is apparent from the figure, most of the reductions in final energy occur in the transportation sector, which relies heavily on vehicles with efficient electric drivetrains under the Medium and High scenarios. Reductions in energy consumption by buildings, mainly by replacing oil- and natural-gas (and electric resistance) heating technologies with heat pumps, is also apparent in the figures.

Although not shown in Figure 7.6 (which presents results from the Moderate technology advancement projections only), Rapid advancements (i.e., more-efficient end-use electric technologies) would lower final energy estimates even further, to 58 quads and 52 quads in the Medium and High scenarios, respectively, in 2050. Conversely, under Slow technology advancements, the energy efficiency benefits of electrification are more muted: 60 quads and 55 quads respectively for the Medium and High scenarios. These results show how electrification can result in increased energy efficiency (at least on a final energy basis), but the level of technology innovation has a measurable influence on the degree to which the benefit would be realized.

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[75] The figure only includes energy consumption tracked on the demand-side of EP and, hence, excludes some important energy-consuming industries and activities, such as fossil fuel extraction and refining. All percentages reported are with respect to the EP-modeled values rather than historical values. Total final energy consumption in 2017 is estimated to total about 72 quads (LLNL 2018).

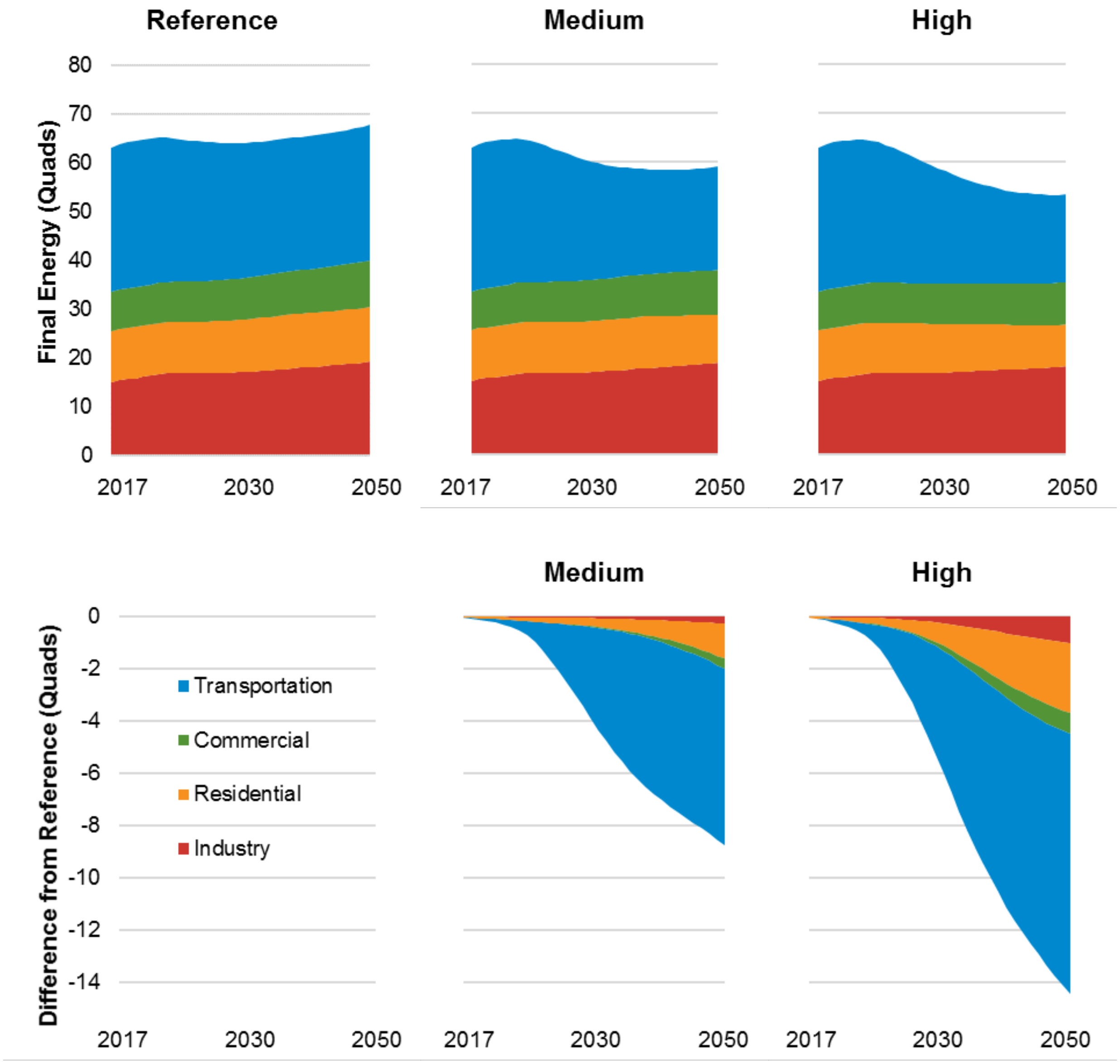

Figure 7.6. Final energy consumption by scenario

Moderate technology advancement projections are shown. Estimates exclude fossil fuel extraction and refining.

Final energy consumption, by definition, does not account for upstream losses from electricity production or transmission and, therefore, does not offer a complete picture of overall energy efficiency. *Primary* energy consumption would also depend on the mix of resources used on the supply-side of electricity generation. Future EFS reports will include a supply-side analysis and will provide assessments of overall fuel and energy consumption.

7.3 Electricity Consumption Profiles

Changes in annual electricity consumption can have important impacts on future electricity supply requirements. However, the temporal characteristics of electricity consumption can have equally critical impacts on power systems planning and the evolution of the U.S. electricity system. Here, we present electricity consumption profiles based on estimates from EP. The methodology for constructing the 8,760 hourly consumption profiles in this model is described in Section 5.2.[76]

Figure 7.7 shows hourly electricity consumption in January and July estimated for 2015 and for 2050 under the core electrification scenarios. Specifically, it shows the "month-hour" average, meaning the value shown for each hour reflects the demand in the same hour averaged across all days of that month. As reflected by the 2015 data, aggregate peak electricity demand in the United States—as well as for many regions therein—often occurs during hot summer afternoons due in large part to air conditioning requirements in addition to other electricity loads that occur year-round. Electricity demand is significantly lower during the other non-summer seasons, including winter. During winter months, daily electricity demand often follows a "double-hump" pattern, reflecting usage patterns for lighting, electric heating, office equipment, and other end uses.

Under the Medium and High electrification scenarios, many of these general seasonal and diurnal features remain. For example, electricity demand is high during summer afternoons as demands for air conditioning services are estimated to grow similarly in all scenarios. However, a notable difference in winter load shapes occurs with greater electrification: increased use of electric space heaters, including ASHPs (with backup electric resistance heating for very cold conditions), raises winter demands faster than in the summer. Figure 7.8 reveals these changes more apparently by showing the electrification-driven and technology-specific incremental electricity demand in the High scenario relative to the Reference for the same two months. The impact on peak winter demands from space and water heating in the residential, commercial, and industrial sectors are clear. In contrast, EP estimates smaller differences in load shapes from vehicle electrification and electrification of all other end uses between seasons.[77] As a result, in the High scenario, *incremental* electricity consumption is in fact higher in January than in July and other non-winter months.

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[76] As part of the EFS, a separate model, referred to as the demand-side grid (dsgrid) model, is also developed with the aim to construct 2050 hourly electricity demand for the scenarios using bottom-up approaches (Hale et al. forthcoming). The sectorally, regionally, and temporally resolved dsgrid results are planned for use in the production cost simulations for future EFS analysis. In this report, we present estimates directly from EP, which are to be used in the electricity supply capacity expansion work for the EFS. Although dsgrid has greater modeling fidelity than EP, it only captures profiles in a single year, whereas the EP analysis can be used to estimate trends over time. Furthermore, the EP estimates are provided for multiple scenarios and therefore can be used to reveal some of the underlying drivers behind the profile changes as presented in the current report.

[77] EP includes some seasonal differences in VMTs. For example, January light-duty charging loads are 83% of those assumed in July.

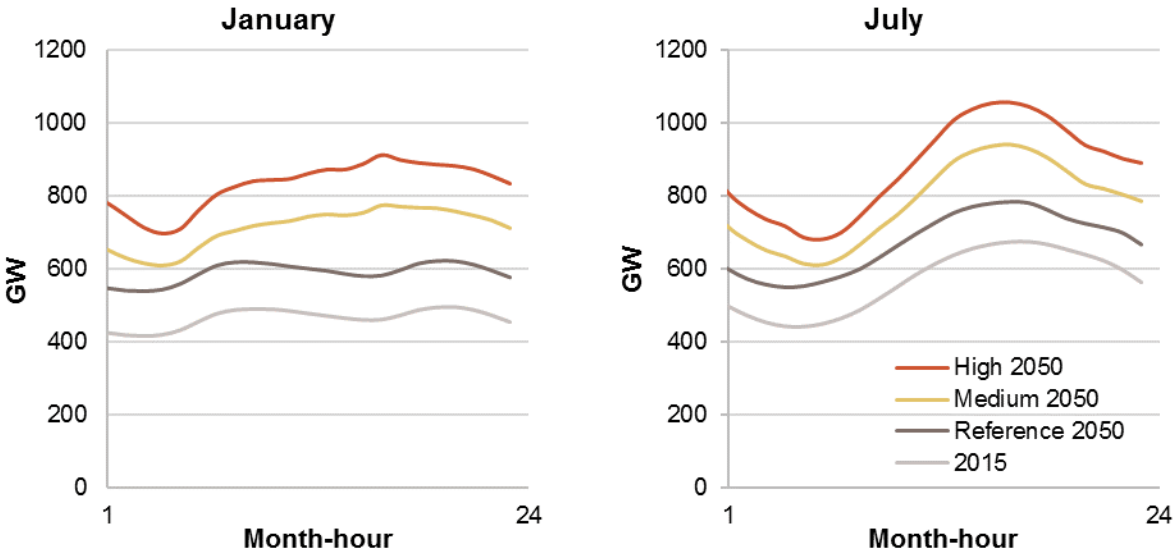

Figure 7.7. Total month-hour power consumption profiles in the core electrification scenarios for January (left) and July (right)

Moderate technology advancement projections are shown. The profiles shown include the estimated impacts of flexible load as modeled in EP.

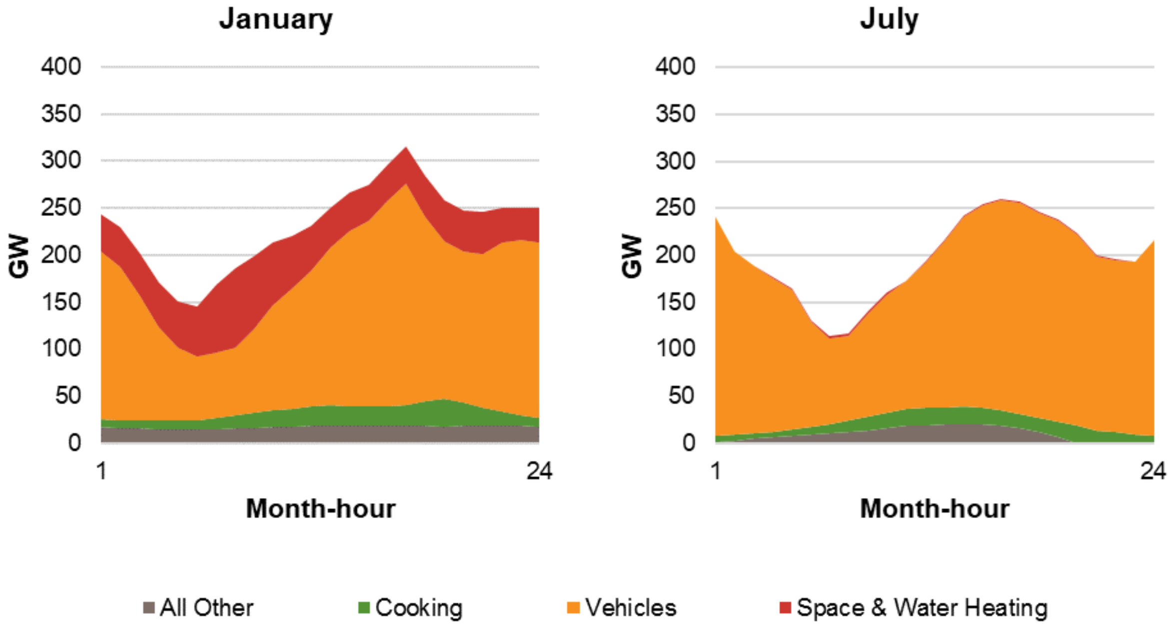

Figure 7.8. Incremental month-hour consumption in 2050 under the High scenario, relative to the Reference, for January (left) and July (right)

Moderate technology advancement projections are shown. The profiles shown include the estimated impacts of flexible load as modeled in EP.

The greater impact from electric space heating, relative to other end use electric technologies, on the timing and magnitude of peak demand results in different regional effects of electrification. Figure 7.9 shows how peak demand grows and shifts to the winter season for an increasing number of states over time in all scenarios—but especially in the Medium and High scenarios.

The size of the pie charts in the figure corresponds to the magnitude of the highest estimated hourly load for each state, and the pie wedges show how the top 100 load hours are distributed across the four seasons. In 2015, all states excluding those in or near the Pacific Northwest are estimated to be summer peaking, with a majority of the top 100 load hours falling in June, July, or August. By 2050 under the Reference scenario, this largely holds; however, a greater fraction of the top 100 peak hours occur during the winter months in the southeastern states. Under the Medium and High electrification scenarios, this trend is most apparent in the northeastern and midwestern states from the use of electric ASHPs in those cold climates. In fact, under the High scenario, nearly all northeastern states become winter peaking by 2050.

Coupled with the shift in when peak demand occurs is an increase in the size of the peak. These changes, shown in Figure 7.9 and discussed below, could have significant impacts on electric utility planning, grid operations, reliability assessments, and electricity markets—issues that will be addressed in future EFS reports.

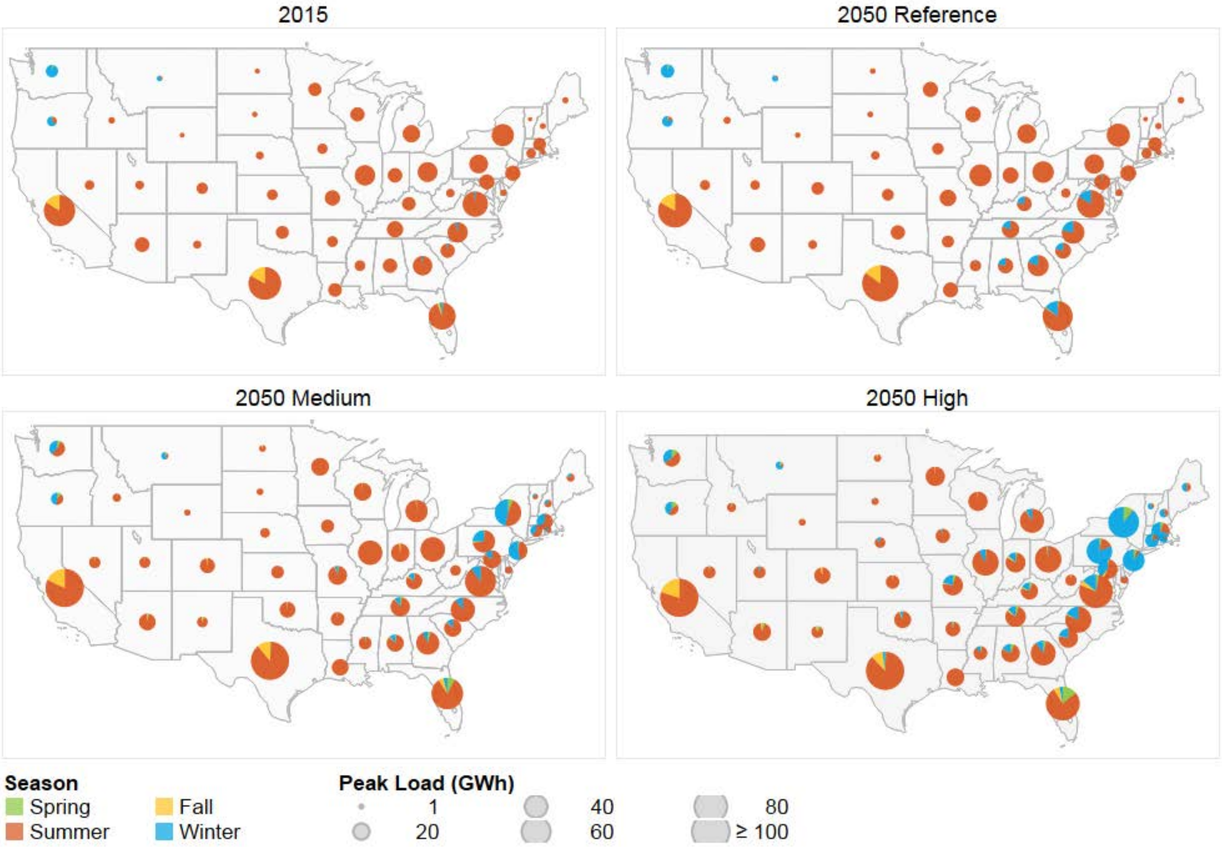

Figure 7.9. Peak load season by state and scenario

The size of the pie charts corresponds with total electricity demand gigawatts (GW) during the top demand hour. The pie wedges show the seasonal distribution of the top 100 hours with the highest demand by state. Seasons are defined along monthly groupings: summer includes June, July, and August; fall includes September, October, and November; winter includes December, January, and February; and spring includes March, April, and May. Moderate technology advancement projections are shown. Data shown, including 2015 data, are based on modeled estimates.

Load duration curves, where hourly electricity demand in a year is ordered from highest to lowest, are common ways to provide a high-level characterization of electricity consumption patterns. Figure 7.10 shows 2050 load duration curves for the three electrification scenarios as well as modeled 2015 demand. These curves reveal how electrification is estimated to increase the hourly aggregate peak demand, which impacts electric utility planning—particularly for maintaining reliability and resource adequacy. EP estimates a 2015 U.S. aggregate peak demand of 717 gigawatts (GW). Under the Reference scenario, we estimate the peak to grow to about 838 GW by 2050. In comparison, under the Medium and High scenarios, 2050 hourly peak demands are estimated to be significantly higher at 997 GW (19% above the Reference) and 1,111 GW (33%), respectively.

Figure 7.10 also shows the load factors—the ratios of average-to-peak demand—for all three scenarios (Reference, Medium, and High). Load factors are estimated to increase over time for all scenarios suggesting a different optimal mix of generation technologies from today as plant utilizations may differ. Although the load factor is estimated to grow in all scenarios, the load factor for the High scenario is estimated to exceed that found in the Reference and Medium scenarios. For context, from 1990 to 2016, the load factor and its inverse, the peak-to-average ratio, has remained steady. This growth indicates that electrification—in combination with the assumed vehicle charging flexibility in our default scenarios (see Section 5)—can result in steadier[78] consumption of electricity and, possibly, more-consistent utilization of power plants and other infrastructure. This finding is qualitatively consistent with prior studies, including Steinberg et al. (2017), which found significant changes in the load factor from electrification but also assumed a much greater degree of vehicle charging flexibility.[79]

The load factor and load duration curves, however, may not reveal how electrification may impact power system operations (e.g., changes in power plant ramping and cycling needs) or power plant investment economics (e.g., increased desirability for flexible generators). For example, the increase in winter peaks may help increase load factors but could also enhance diurnal peak-to-trough ratios, which are not observable by estimated annual load factors or load duration curves. Furthermore, regional consumption patterns are impacted differently by electrification, as discussed previously. Planned research in the EFS is intended to address these issues and the interactions with various supply-side futures. Nonetheless, the results presented here highlight that electrification can substantially change electricity consumption patterns in many regions.

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[78] The metric does not measure the hour-to-hour or day-to-day variations in demand but examines only how the annual peak demand compares with the annual average.

[79] In addition to flexible electric vehicle charging, Steinberg et al. (2017) included higher penetrations of fuel cell vehicles and assumed the electrolysis-based hydrogen production was sufficiently flexible to avoid any incremental vehicle-driven peak electricity demand growth.

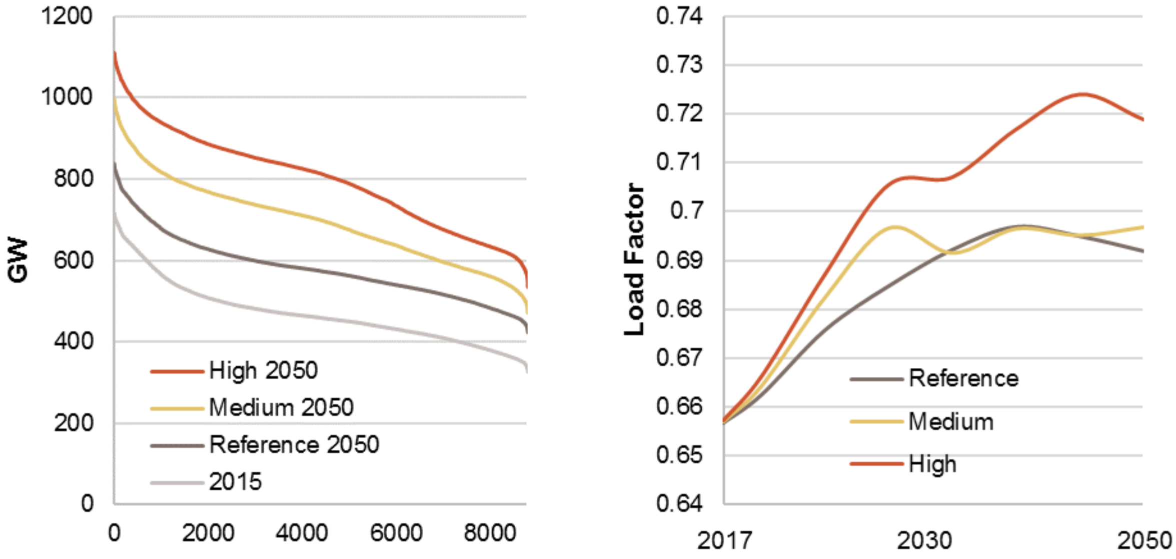

Figure 7.10. Load duration curves (left) and load factor over time (right) for the core electrification scenarios in 2050

Moderate technology advancement projections are shown.
The profiles shown include the estimated impacts of flexible load as modeled in EP.

The findings reported above can be sensitive to several factors. The method used to generate the demand profiles rely on many assumptions and uncertain factors that are not fully accounted for in the EP methodology. We highlight several issues that will likely affect how electrification might impact electricity consumption profiles but which require more research. First, electricity demand can be sensitive to future electricity prices and rate structures and electrification can sway (or be swayed by) rate design. Second, the potential increase in demand-side management and demand-response to provide grid services could be enabled with electrification and could dramatically impact load shapes—particularly to reduce peak demands.[80] The same applies to energy storage technologies, including distribution-sited, behind-the-meter, or integrated within end-use devices. Third, limited data exists for electricity consumption patterns of new electric technologies or end uses, such as HDVs or industrial electrotechnologies, making it difficult to model electricity use with increased electrification for these end uses. Fourth, dramatic changes in behavior or technology, such as autonomous vehicles, could change consumption patterns. Finally, changes in weather patterns and demographics could alter hourly electricity consumption. A comprehensive analysis of all these issues is beyond the scope of this report and the broader EFS. However, we conduct a simple sensitivity analysis covering a broad range of demand-side flexibility levels in Section 7.4.

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[80] Future EFS analysis and the tools and data developed in EFS are planned for use to study this question.

7.4 Demand-Side Flexibility Sensitivities

Consumption profiles are determined not only by the type of equipment adopted by end uses, but also by how that equipment is operated. In this section, we examine how these profiles might change with different levels of demand-side flexibility, which is narrowly defined here as the ability to shift electricity consumption from one period to another. This narrow definition and the limited extent to which we explore possibilities for demand-side flexibility warrant a note of caution in interpreting the following results. In particular, although we present sensitivities to understand the directional impacts of demand-side flexibility, more research is needed to quantify the value of this flexibility. Future EFS reports will provide additional insights beyond the limited exploration described below.

The EP method for representing demand-side flexibility is described in Section 5.2. Overall, the method assumes that a certain amount of flexible equipment penetrates the end-use technology stock in a year and that this energy consumption may be shifted forward or backward in time some amount, depending on the end use. The electricity consumption results presented in Section 7.3 relied on a default representation of demand-side flexibility, which assumed flexibility from electric light-duty cars and trucks only. Under the default conditions, we assume a possible charging delay of up to five hours for 75% of the light-duty PEVs by 2050. The penetration of flexible equipment for vehicle charging is assumed to increase linearly from 50% in 2015, which is intended to match historical charging behavior influenced by time-of-use rates and other factors. Based on these constraints, vehicle charging decisions are made by the dispatch optimization in EP. These assumptions for flexible charging of PEVs is one of the reasons we estimate increasing load factors in the High scenario.

To test the sensitivity of our electricity consumption results to a range of flexibility conditions, we model two additional scenarios (Low Flexibility and Enhanced Flexibility), both with High adoption and Moderate technology advancement levels. In the Low Flexibility scenario, we assume consumption profiles are based on the native assumptions used in EP for the level of demand-side flexibility in 2015 for all years. In the Enhanced Flexibility scenario, we assume additional flexibility in electric LDVs by increasing the penetration of flexible charging from 75% to 90% in 2050. In addition, we assume additional flexibility capabilities in HVAC systems and water heating equipment for both the residential and commercial sectors. The buildings demand-side flexibility is implemented similarly to vehicle flexibility within the EP modeling framework. A notable difference is that we assume both advanced (e.g., pre-cooling) and delayed electricity use in buildings whereas vehicle charging can only be delayed. Section 5.2 provides details on the flexibility parameterization for these two sensitivity scenarios.

The results from this sensitivity analysis suggest flexibility can decrease peak loads and increase load factors. In particular, we find that the aggregate and coincident peak load in the Low Flexibility is over 13 GW higher than in the default case, which included flexibility in LDV charging. In the Enhanced Flexibility scenario, the additional flexibility, in both vehicle charging and through smart energy management systems implemented in buildings HVAC technologies, can help reduce peak demands by another 4 GW. In terms of load factors, these sensitivities indicate that the incremental flexibility can lead to increases in load factors by up to about 2%.

These two effects could help avoid construction of unnecessary peaking capacity[81] and increase utilization of existing capacity. Although seemingly modest in magnitude relative to the overall system, the avoided capacity could help reduce billions of dollars in system expenditures, which presumably would be passed on to consumers. Similarly, the increased plant utilization could mean the difference between sufficient revenues to continue operations and retirement for certain units.

It is important to note that none of the scenarios considers the full extent that flexibility might be available from the demand-side. For example, we only model flexibility from vehicle charging for the light-duty fleet, whereas flexibility from larger trucks and fleets might enable even more optimal charging possibilities—including the amount of energy (megawatt-hours) that can be shifted and the duration over which this shift is possible (hours). Furthermore, although we modeled flexibility only in terms of the degree to which electricity use can be advanced and/or delayed, flexibility can also come from various other capabilities and can provide other system value. These include the use of interruptible load to manage peak capacity needs, the provision of ancillary services, and the deferment of transmission and distribution equipment upgrades. The flexibility sensitivities do not cover this full range, and they likely underestimate the impacts of (and value of) demand-side flexibility. While inconclusive, the results of the sensitivity analysis highlight the directional impact that demand-side flexibility could have on load shapes, particularly with widespread electrification.

Further analysis of the interactions of electrification and demand-side profiles and flexibility are planned for the EFS. In particular, a new model, referred to as the demand-side grid (dsgrid) model (Hale et al. forthcoming), is designed to apply bottom-up modeling to assess future electricity consumption patterns with higher fidelity than is possible with EP. Using this model and high-resolution resource adequacy and dispatch models, the impacts of increased demand-side flexibility to consumption profiles and supply-side evolution and operations could be explored. Of course, the cost and value of demand-side flexibility will also depend on a host of other factors that may not be easily assessed by the planned modeling analysis. These factors include market rules for demand-side participation in electricity markets, retail rate structures, and behavioral factors. Furthermore, more research is needed on "enablement" costs and consumer willingness to participate in demand-side flexibility programs to assess the relative aggressiveness of these sensitivities. Nonetheless, electrification can increase the amount and type of resources from the demand-side that *could* provide system flexibility. Further research is warranted to quantify the extent to which additional flexibility provides value to both the power system and consumers.

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[81] The exact amount of avoided capacity, and therefore value, of the flexibility is difficult to assess, as it will depend on any possible excess capacity in the default case, resource adequacy targets, and coincidence of peaks.

8 Discussion

In this report, we presented scenarios with various degrees of future electrification in all major end-use sectors of the U.S. energy system—including transportation, residential and commercial buildings, and industry—through 2050. The scenarios were used to characterize the impacts of an electrification transition in terms of equipment sales and stock as well as to quantify how electrification might impact electricity demand, consumption profiles, and energy use. Adoption levels in the scenarios were developed primarily by expert judgment from the authors based on analysis of current trends and insights from other studies, but we also relied on consumer choice models in select instances. Moreover, the scenarios covered a wide range of uncertainty along two dimensions: the adoption penetration of end-use electric equipment and the rate of technology advancement for select technologies. Figure 8.1 summarizes annual electricity consumption estimates for the three core adoption levels modeled (all using the Moderate technology advancement projections) and compares these estimates with available historical data. Figure 8.2 summarizes comparisons for the same three scenarios with historical estimates, but in terms of electricity share of final energy.

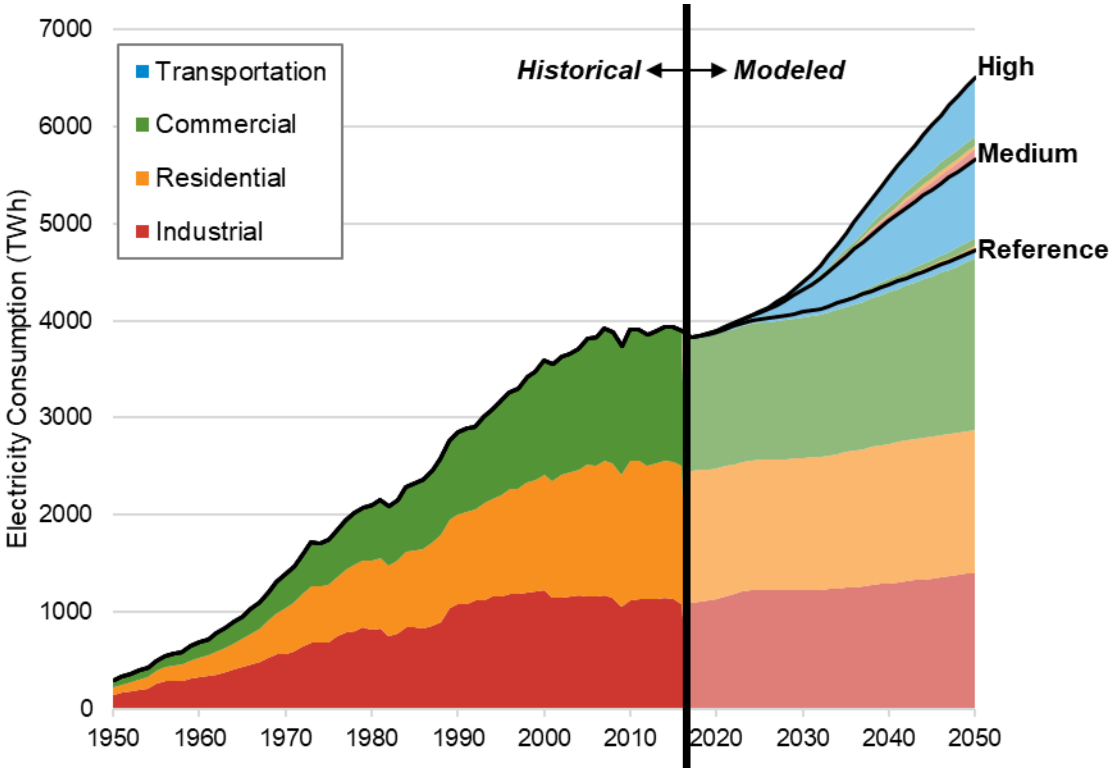

Figure 8.1. Historical and projected annual electricity consumption

Moderate technology advancements are shown. Slight adjustments were made to the modeled industry consumption estimates (for 2017-–2020) to align them with available historical data.

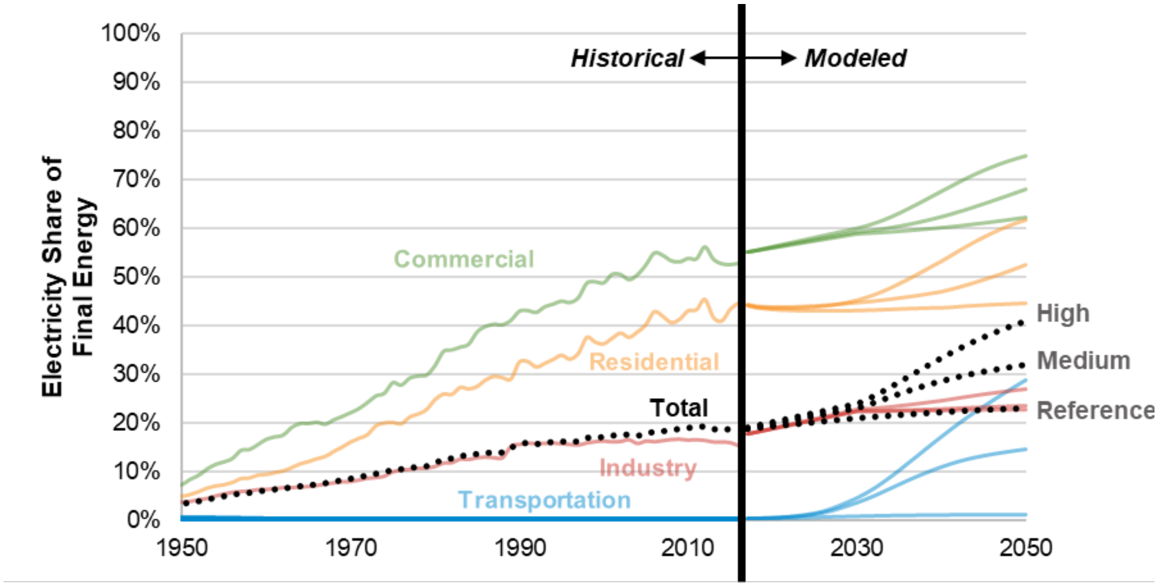

Figure 8.2. Electricity share of final energy consumption

Moderate technology advancements are shown. Historical and modeled data have slightly different scope and therefore are not fully comparable. Notably, modeled data omits fossil fuel extraction and refining. However, differences amount to only a few percentage points between the 2016 historical data and the 2017 modeled data. Visual adjustments and interpolations were used for the modeled data (for 2017—2030) in the figure shown.

The following quantifications from the analysis help to characterize an electrification transition:

- Widespread electrification requires accelerated equipment sales that are well beyond current levels, but equipment longevity can slow stock turnover. In the High scenario, the U.S. on-road transportation fleet included 240 million light-duty PEVs, 7 million medium- and heavy-duty plug-in electric trucks, and 80,000 battery electric transit buses that, together, deliver up to 76% of vehicle miles traveled from electricity in 2050.

- A dramatic change in electric buildings appliance manufacturing and adoption is needed in our scenarios, as the electric equipment are found to provide up to 61% of all space heating, 52% of all water heating, and 94% of all cooking services in the combined commercial and residential sectors by 2050 in the High scenario, compared with 17%, 26%, and 34%, respectively, in the Reference scenario.

- In the same scenario, the adoption of various industrial electrotechnologies are found to provide 63% of curing needs, 32% of drying services, 56% of other process heating, and a range of other industrial end uses.

- In 2050, electricity share (of total final energy) in the scenarios increased to 32% in the Medium and 41% in the High scenario—significantly above the 23% in the Reference scenario and 19% in 2016.

- Electrification leads to reduced domestic on-site use of gasoline, diesel, and natural gas fuel. Demand-side fuel use reductions of 74% gasoline, 35% diesel, and 37% natural gas in 2050 were found in the High scenario, relative to the Reference. These fuel savings could have important impacts on power generation economics, global energy markets, energy security, and geopolitics.

- Advanced electric technologies are often more energy efficient than competing options that provide the same end-use services. This greater energy efficiency resulted in 13% reduction in 2050 final energy consumption in the Medium scenario, relative to the Reference, and 21% in the High scenario, even as electricity consumption grows with electrification.

- Widespread electrification could increase 2050 U.S. electricity consumption by 932 TWh (20%) and 1,782 TWh (38%) for the Medium and High scenarios, respectively and relative to the Reference, with compound annual load growth rate (2016 to 2050) of 1.6% found in the High Scenario. Absolute and non-compounding year-to-year changes in consumption in the Medium and High scenario averaged (during 2016–2050) 55 TWh/yr and 80 TWh/yr, respectively, compared with 50–55 TWh/year over the prior 34 years and from 2016 to 2050. Incremental annual electricity consumption is dominated by vehicle electrification.

- In the scenarios with greater electrification, incremental increases in peak demand are estimated be lower than the relative increases to annual consumption. In the Medium and High scenario, the aggregate and coincident U.S. hourly peak demands are 19% and 33% higher, relative to the 838 GW peak found in the Reference scenario for 2050.

- Electrification could also dramatically change consumption profiles. Winter peaking demands increase most significantly from electric heat pumps, despite their small impact on annual consumption. In the High scenario, by 2050, nearly all states in the Northeast join the northwestern states and become winter peaking. Winter high demand hours also become much more prevalent in numerous other eastern states.

- Demand-side flexibility can alter consumption profiles and could offer additional value to the grid. Electrification could help enable this additional source of grid flexibility. Impacts of flexibility on grid evolution and operations will be explored in future EFS analyses.

Overall, our analysis found possibilities for end-use electrification in all major sectors; however, adoption would ultimately depend on a set of complex considerations. The factors that could influence adoption include technology and fuel cost trade-offs, infrastructure needs, environmental policies, consumer preference, and interactions between these factors. In this report, we qualitatively discussed the drivers and barriers to electrification, which are implicitly revealed in the scenarios. Insights to specific opportunities and challenges in each sector include:

- **Transportation:** Plug-in electric vehicles offer significant adoption opportunities for all on-road transportation modes, but the greatest impact to the energy system was found for light-duty cars and trucks in part because of their substantial contribution to vehicle miles traveled, fuel use, and emissions. Electrification of passenger vehicles also faces lower technological hurdles than medium- and heavy-duty freight applications due to battery cost and density challenges as well as charging infrastructure and performance needs. However, short-haul freight transport also offers significant electrification opportunities particularly due to the regularity of routes and the fleet-wide coordination that might reduce charging infrastructure-related challenges. The larger fuel consumption of heavier trucks and air quality considerations in urban settings also might motivate electrification beyond the light-duty sector. For the same reasons, transit buses are becoming prime candidates for electrification especially as battery and overall electric vehicle costs decline.

- **Buildings:** Both residential and commercial buildings already rely heavily on electric technologies. However, for certain regions and end-use services, electrification could have a major impact. In particular, highly energy efficient heat pumps for space and water heating, and their ability to provide both heating and cooling or in other integrated systems, have the potential for widespread adoption. Further improvements to the cost and performance of electric heat pumps, especially in colder climates, may be needed to improve their economic viability to a broader range of consumers to yield far-reaching uptake. Furthermore, beyond economic factors the success of further electrification in buildings might hinge on consumer—as well as equipment manufacturer, distributor, and installer—comfort with and preference for new electric technologies. Substantial challenges associated with the retrofit of existing buildings would need to be overcome to enable a rapid transition.

- **Industry:** Limited data and analysis are available to identify electrification potential in the industrial sector, in part, due to the heterogeneity of industrial processes. Significant advancement in depicting process-level detail by industry is needed to improve the analytical rigor of modeling U.S. industrial energy use. Despite these limitations, a focus on identifying and quantifying the productivity benefits of industrial electrotechnologies, and incorporating the value of these benefits into capital investment decisions could yield greater electrification in U.S. industry. Productivity benefits in drying and curing could potentially bring electrification to these processes.

To provide additional context for the prospective electrification scenarios presented, the report included a description of historical electricity consumption trends as well as a characterization of past energy transitions. This retrospective context shows that, although the electrification transition found in many of the scenarios would require substantial change in end-use energy consumption and technology adoption, similar or even more-rapid transitions have occurred in the past. The rate of diffusion might even be higher today, given the increasing spread of information through social media, the internet, and targeted marketing of new technologies. On the other hand, end-use electric technologies that simply displace existing fuel-based options without providing additional value or services might not be adopted as rapidly compared with historical energy and technology transitions observed. In terms of historical electricity consumption, we note that the growth rates even in our highest electrification scenarios are not unprecedented and are well below growth rates that U.S. electric utilities have experienced over their long history. In fact, the modeled growth rates in our prospective scenarios fall below historical growth rates over the same duration (34 years) as our study period.

Looking forward, further research is needed to more comprehensively assess the drivers and impacts of electrification. Although this report focuses solely on the demand-side of the U.S. energy system, future EFS reports will evaluate the potential evolution and operation of future U.S. electricity supply to power the end-use transition presented herein. In other words, the scenarios in this report provide a foundation to more fully assess the impacts of widespread electrification to electric system infrastructure and how that system might be optimally operated to produce low-cost and reliable electricity to meet the new (and old) electric loads. Furthermore, future EFS analyses will evaluate some of the key costs and impacts of electrification futures for both the supply and demand side. This series of analyses, collectively, is intended to advance our understanding of electrification in the United States. For further information about the study, see www.nrel.gov/efs.

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Appendix A. Non-Electric and Non-Direct Electric Technologies

Appendix Authors: Thomas Jenkin and Mark Ruth (NREL)

The EFS analyzes scenarios with various levels of electrification and focuses on direct electric technologies only. This scope omits other potential energy sources and energy carriers. This appendix summarizes published studies that include a broader set of options. Many of these studies examine scenarios with significant energy transitions, including decarbonization strategies; however, as we note in this report, electrification and transitions to other fuels can result from myriad factors.

This appendix summarizes the scenario literature focusing on where non-electric fuels and technology alternatives are used in each of the three sectors—residential and commercial buildings, transportation, and industry. The primary outcome of the literature review is Table A.1, which matches sector and subsector with non-direct electric fuel by study. Note that this review focuses solely on the end-use sectors and does not include how the different fuels are used for power generation in the various studies examined. The table categorizes the non-direct electric fuels into eight types:

- synthetic gas (syngas)
- hydrogen
- nuclear
- pipeline gas
- carbon capture and sequestration (CCS)
- biofuels
- energy efficiency
- other types.

In addition to being alternative (non-conventional) options to electrification, some of these types can also influence the level of electricity consumption. For example, increased energy efficiency could reduce electricity consumption and hydrogen production, using electrolysis, can do the opposite. This appendix, and the broader EFS, make no attempt to examine these interactions or compare the competitiveness of these different fuel types. Instead, the appendix simply provides a literature review of scenarios where non-direct electric fuels are projected to grow.

Table A.1. Non-Direct Electric Fuels by Subsector Considered in Study

Subsector	Syngas	Hydrogen	Nuclear	Pipeline Gas	CCS	Biofuels	Energy Efficiency	Other
Transportation Sector								
Unspecified and/or All		[1],[a] [2]				[3], [4], [5],[a] [1],[a] [6], [7]	[8]	
Medium/Heavy Duty		[8], [9]		[8]		[8], [1],[a] [10][b]	[3]	
Light Duty		[8], [13,] [3], [9]					[3], [11]	[12]
Air		[3], [9]				[3], [13]		
Rail		[8]		[8]				
Industrial Sector								
Unspecified and/or All	[10], [2], [1]		[10]		[3]	[3], [4], [1][a]		[3]
Iron/Steel		[1]		[8]	[9], [14]	[14]	[14]	[14], [1], [8]
Textile								
Cement		[17}			[9], [14], [1]	[9], [14]		
Paper/Pulp						[9], [1],[a] [14]	[14]	[14]
Chemicals	[14], [15]					[1][a]	[14], [1]	
Glass	[14]	[15]			[14], [1][a]		[14]	[14]
Oil/Gas Refining					[1][a]	[9]	[1][a]	
Ceramics	[14]				[14]	[14]		
Buildings Sector								
Unspecified and/or All							[2]	
Residential						[3]	[12], [16]	

[a] Canada, [b] Biodiesel

[1] Bataille, Melton, and Stiebert 2016, [2] Benndorf et al. 2014, [3] The White House 2016, [4] Shinnar and Francesco 2006, [5] EPRI 2018, [6] Harvey 2013, [7] Muratori et al. 2017, [8] Williams et al. 2015, [9] Shell 2016, [10] Demick 2010, [11] Hao, Geng, and Sarkis 2016, [12] Hausker et al. 2015, [13] Wise, Muratori, and Kyle 2017, [14] UK DECC 2015, [15] WSP-PB 2015, and [16] Vásquez et al. 2016

Appendix B. Transportation Technology Adoption

Appendix Authors: Paige Jadun, Matteo Muratori, Laura Vimmerstedt, and Aaron Brooker (NREL)

Development of the EFS Reference, Medium, and High electrification scenarios for the transportation subsectors is based on a combination of expert judgment, a literature review, and results from LDV consumer choice models. The ultimate adoption of electric vehicle technologies will depend on various factors, including future vehicle cost and performance, charging infrastructure buildout, duty cycle requirements, policy support, consumer preferences, availability of models, and additional non-economic influences (e.g., brand loyalty and environmental motivation) that contribute to consumer choice.

Because of their large share of energy use and emissions, and the more mature market stage, electrification of LDVs has received more attention, both in terms of analysis (e.g., Elgowainy et al. 2016; Kim et al. 2006; Wang et al. 2017; Yang et al. 2009) and modeling tools, including vehicle choice models (Stephens et al. 2017). For the non-light-duty subsectors, literature and modeling tools regarding electrification potential are sparse, and the studies that do exist find that transformations from the status quo are generally more difficult than those of the light-duty sector (Muratori et al. 2017; Girod et al. 2013).

In this study, we align the Reference electrification scenario with the AEO2017 Reference case (EIA 2017c). Electrification in the Medium scenario is informed using NREL's vehicle consumer choice model, Automotive Deployment Options Projection Tool (ADOPT), for the light-duty subsector and by expert judgment for the medium- and heavy-duty segments. The use of a consumer-choice model, such as ADOPT, provides a grounded projection that considers the many aspects of consumer purchase decisions. The High scenario is a "what-if" case designed to explore great success of all electrification technologies in all on-road transportation subsectors, and it may include effects of disruptive technologies or structural changes in the sector that would not be fully captured in the current ADOPT framework. Section B.1 details the use of ADOPT to develop the Medium LDV adoption scenarios (and to loosely inform the High scenario), and Section B.2 describes the assumptions used in the Medium and High scenarios for MDVs and HDVs.

B.1 Light-Duty Vehicle Choice Modeling

ADOPT is a vehicle consumer choice and stock model that estimates future U.S. LDV sales. NREL developed it to estimate the impacts of targets for automotive technology improvement in terms of greenhouse gas emissions and petroleum consumption (Brooker et al. 2015a). To do so, ADOPT considers temporal variation of technology cost and performance, fuel prices, and fueling station availability impacts, which results in new vehicle attributes. The model uses a mixed-logit method to trade off these new vehicle attributes and project sales for different vehicle types and models for various income distributions. This method weights a set of coefficients (e.g., cost, volume, acceleration, and range) to capture consumer preference heterogeneity. These coefficients, which are non-linear and vary with income, are calibrated based on historical sales. ADOPT represents each make and model of vehicle that is sold today, providing a diverse range of realistic vehicle characteristics, which is important for calibrating the choice model because most advanced vehicles have acceleration and pricing that is not consistent with average vehicles. The model has been extensively validated on a set of metrics, including sales by powertrain, vehicle class, price, acceleration, and fuel economy.[82] ADOPT propagates new vehicle make-model-trim combinations based on sales success, enabling modeling of availability of advanced vehicle drivetrains in the future vehicle fleet. To do so, ADOPT uses FASTSim (Brooker 2015b), a powertrain model, to evolve future vehicle options based on market driven component sizing. The propagation and sales of new vehicles in ADOPT also take into account policies, such as the Corporate Average Fuel Economy (CAFE) and greenhouse gas standards. ADOPT employs engine downsizing, technology improvements, and incentives and penalties to drive sales to conform to the regulations. Main inputs to the model are future component-level technology cost and performance (e.g., battery, engine, motor, and fuel cell costs, peak engine efficiency, lightweighting, and battery energy density) as well as fuel prices and total vehicle sales and policy stringency. Figure A1 shows a representation of ADOPT and its interaction with FASTSim.

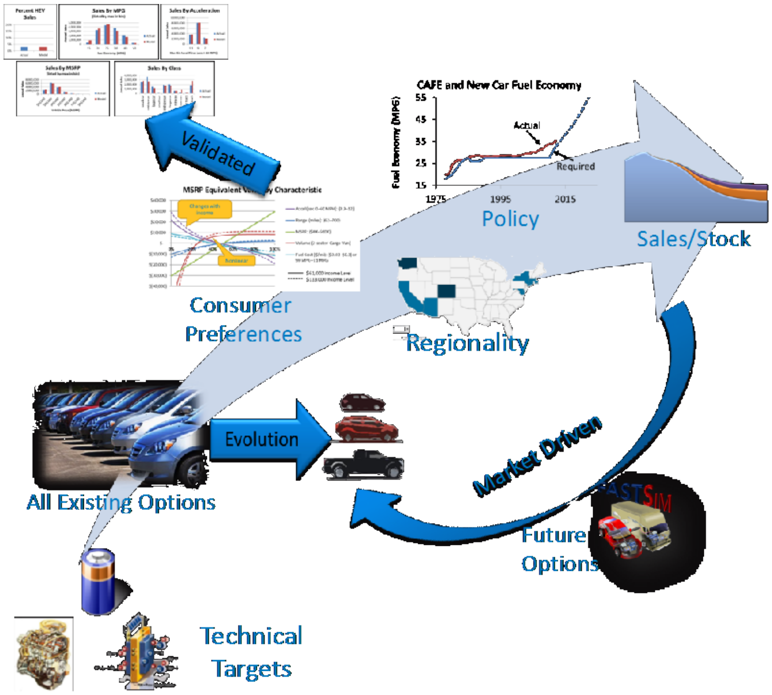

Figure B.1. Schematic of the Automotive Deployment Options Projection Tool (ADOPT)

ADOPT estimates technical target impacts on greenhouse gas emissions and petroleum consumption based on five steps: (1) The model starts by representing all makes and models of vehicles available today for vehicle diversity and realism. (2) It then trades off vehicle attributes using consumer preference relationships that provide matching sales with historical data in many different dimensions. (3) It calculates the CAFE and greenhouse gas regulations and duplicates market approaches to meeting them. (4) Sales estimates are used to evolve future vehicle options based on market driven component sizing using the integrated powertrain model FASTSim. (5) Finally, the sales go into a stock model to estimate total fleet greenhouse gas emissions and energy consumption.

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[82] A subset of past sales data is used to calibrate the impact of the different attributes on consumer choice, and a different subset of sales data is then used to validate the model output.

The input assumptions and resulting vehicle sales shares used for the Medium scenario are described below. The key technology inputs for PEV adoption are battery performance and cost. For the Medium scenario, we rely on the technology assumptions in the 2015 DOE Vehicle Technologies Office (VTO) Government Performance and Results Act (GPRA) analysis (Stephens et al. 2016; Stephens, Birky, and Gohlke 2017).[83] We assume the non-electric vehicle technologies follow a low technology improvement trajectory that corresponds to the 2015 GPRA No Program case, which assumes no technology improvement or cost reductions due to the DOE programs after 2016. The assumptions for most electric vehicle technologies, including batteries and electric motors, follow the higher technology improvements from the 2015 GPRA Program Success case, which reflects technology performance and cost goals from the VTO, with one exception. The battery cost assumptions used in EFS align with the Moderate advancement trajectory documented in the first report of the EFS series (Jadun et al. 2017), which assumes battery costs reduce to $135/kWh in 2050 (Moawad et al. 2016). Vehicle deployment modeled in ADOPT also depends on the relative fuel costs based on efficiency improvements and the AEO2017 Reference case fuel price projections. A sensitivity on fuel prices is included in the results below. The input used in the Medium scenario assumptions are summarized in Table B.1.

Table B.1. Inputs Assumptions for the Medium Scenario

	ADOPT Input	Scenario Assumptions
Fuel Prices	Gasoline	Price trajectory from AEO2017 Reference case (EIA 2017c)
	Electricity	Residential price trajectory from AEO2017 Reference case (EIA 2017c)
	Hydrogen	Constant price based on current national average (DOE 2017)[a]
Technology Improvement	Battery Cost	Moderate advancement trajectory in Jadun et al. 2017
	Other EV Components	Program Success case in GPRA 2015 (Stephens et al. 2016)
	Non-EV Components	No Program Success case in GPRA 2015 (Stephens et al. 2016)

[a] The price estimate is based on a small sample size of 10 points, with an average price of $15.04 per gallon gasoline equivalent.

Using the input assumptions described above, we use ADOPT to estimate future LDV sales in the United States through 2050. The results include sales by five powertrain types:

- Conventional internal combustion engine vehicles (divided between diesel and gasoline)
- hybrid electric vehicles (HEVs)
- Fuel-cell electric vehicles

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[83] We use assumptions from GPRA 2015 to maintain consistency with the vehicle cost assumptions documented in Jadun et al. (2017) but note that a more recent GPRA analysis has been published since (Stephens et al. 2017).

- Plug-in hybrid electric vehicles (PHEVs)
- Battery electric vehicles (BEV).[84]

For the EFS, we input the resulting sales share percentages to the EnergyPATHWAYS (EP) accounting tool. Figure B.2 shows the modeled vehicle sales shares by powertrain for light-duty cars and trucks through 2050. The results show a transition away from conventional vehicles to primarily PHEVs and BEVs, which make up 63% of car sales and 69% of truck sales by 2050.[85] The increase in PEV sales shares primarily occurs through 2030 and then levels off. This projected trend reflects the effects of the CAFE requirements, which increase through 2025 then remain constant through 2050. PEVs have a fuel economy advantage over conventional vehicles because of CAFE incentives in the near term, and in the long term, they compete with HEVs on fuel cost and acceleration. We note that under alternative assumptions on fuel price, technology improvement, and infrastructure availability, ADOPT generates different results than those shown here.[86]

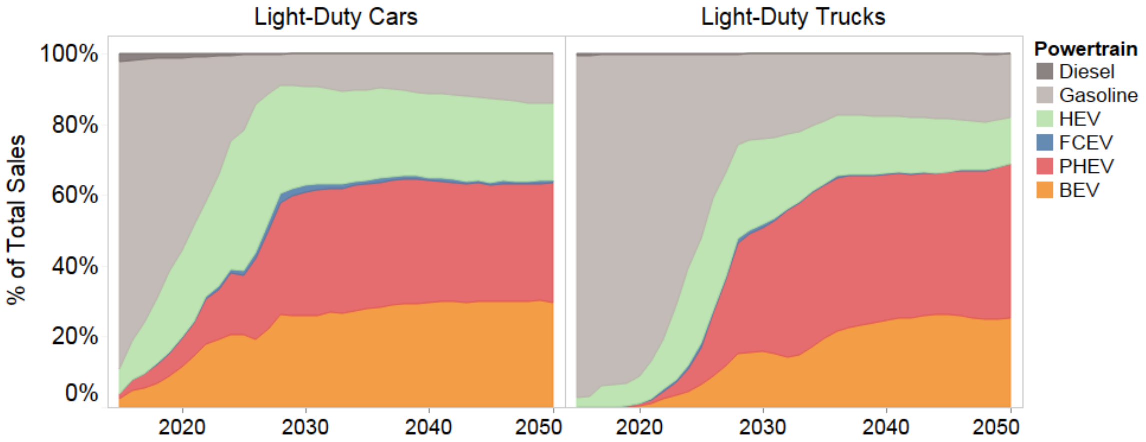

Figure B.2. ADOPT light-duty car and light-duty trucks sales shares trends for the Medium scenario

The sales estimated in ADOPT depend on the relative attractiveness of available vehicle models across a variety of factors, including cost, additional vehicle attributes, and fueling infrastructure availability. These tradeoffs are illustrated in Figure B.3, which shows the sales and relative generalized cost by vehicle attribute for the bestselling cars by powertrain in 2025 and 2050, for the $133,000 annual household income level (under the Medium scenario). The gray stacked bars in the background represent the vehicle sales by income level (left y-axis), and the colored bars represent the MSRP-equivalent vehicle total perceived cost including all the attributes weighted by ADOPT (right y-axis). The higher the MSRP-equivalent vehicle total perceived cost, the lower sales will be. These bars essentially summarize all the attributes considered by ADOPT and their impact on the overall attractiveness of a vehicle. For example, Figure B.3 shows that in 2025 the bestselling HEV slightly outsells the bestselling PHEV because of its lower price, despite the greater CAFE incentive and increased acceleration of the PHEV.

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[84] ADOPT also models compressed natural gas vehicles, but they make up less than 1% of sales and are excluded from the displayed results.

[85] PHEV exceeds BEV adoption among light trucks, whereas the reverse is true for cars. Relative battery costs and fuel savings explain this difference.

[86] This may include higher penetrations non PEV technologies, such as HEVs and fuel-cell electric vehicles.

The bestselling BEV outsells all other powertrains, especially for high-income drivers, because of its even better CAFE incentive and acceleration. In 2050, CAFE incentives have a much lower impact, and the relative attractiveness of PEVs is driven primarily by acceleration and fuel cost savings; the impact of range also decreases over time, as ADOPT projects increasing battery sizes because of reducing battery cost.

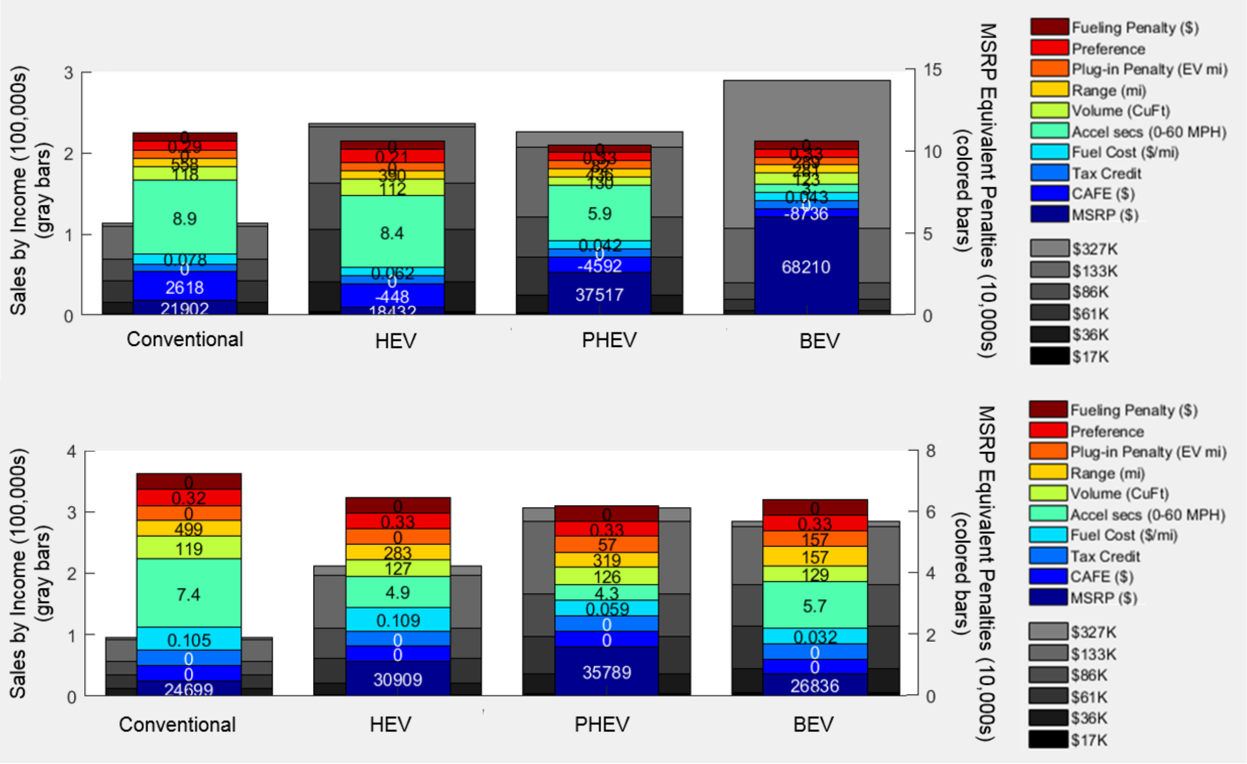

Figure B.3. Attribute comparison of the bestselling light-duty cars by powertrain in 2025 (top) and 2050 (bottom)

Changes to the input assumptions can impact the projected sales shares in ADOPT to varying degrees. We include a sensitivity analysis of the vehicle technology inputs and fuel prices used for the Medium scenario to highlight their impacts on the results. Figure B.4 shows the effect of various battery cost assumptions (from Jadun et al. 2017) on the aggregate car and truck sales shares. As expected, slower battery improvement most significantly affects the sales of BEVs. Sales shares of BEVs in 2050 drop from 38% in the Rapid advancement scenario to 27% in the Moderate advancement scenario (which is used for the Medium scenario), and 17% in the Slow advancement scenario. PHEV sales replace BEV sales in scenarios with less battery advancement, with PHEV sales shares increasing from 35% when using the Rapid advancement case to 39% and 44% in the Moderate and Slow Battery advancement cases, respectively. The final adoption of conventional vehicles (with stand-alone internal combustion engine drivetrains only) remains relatively constant across scenarios, but sales of HEVs increase with battery costs, as they become more competitive with PHEVs and fill the need for more fuel-efficient vehicles that is driven by the modeled regulations. In addition to overall sales and the PHEV/BEV split, vehicle attributes estimated by ADOPT, such as the all-electric range for PHEVs and BEVs, also vary with battery cost assumptions, as shown in Figure B.5. For slower battery cost improvements, the market shifts toward shorter range vehicles. For example, in the Slow Battery

Advancement case, the BEV-100[87] dominates BEV sales, but longer-range vehicles reach greater adoption with more-rapid battery advancement.

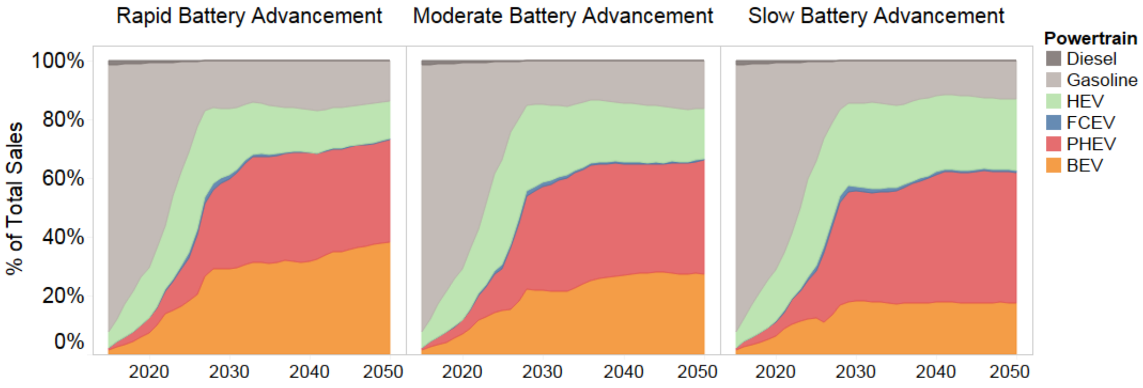

Figure B.4. Sensitivity of vehicle sales shares to battery cost assumptions

The Medium scenario uses the Moderate Battery Advancement projection.

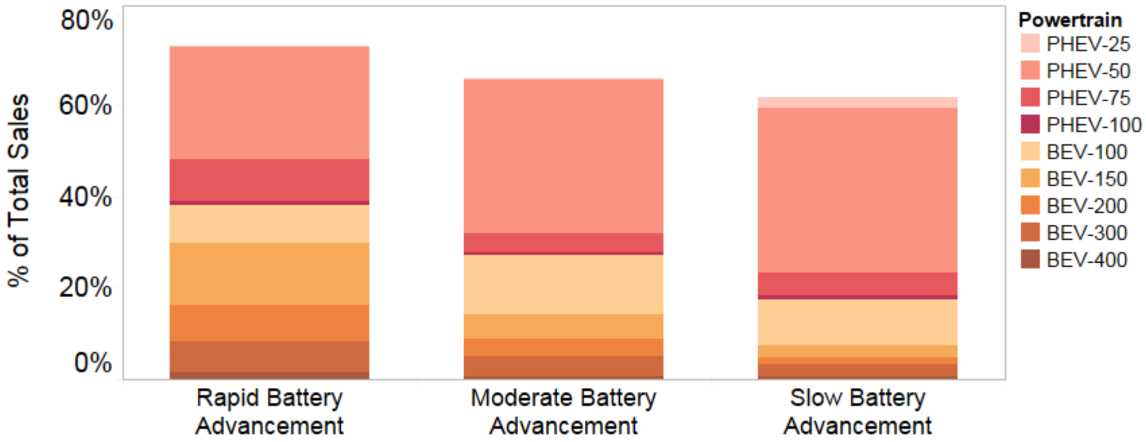

Figure B.5. Sales shares of PEVs in 2050 by all-electric range

The Medium scenario uses the Moderate Battery Advancement projection.

Figure B.6. shows sales results from additional sensitivity scenarios. The High Non-EV Technology Advancement scenario assumes all technologies, and not just those related to PEVs, follow the high technology improvement trajectory, which corresponds to the Program Success case in the 2015 GPRA, and the Low Oil Price scenario uses fuel prices from the AEO2017 Low Oil case. When all technologies follow high advancement trajectories, the resulting adoption of PEVs in 2050 declines from 73% in the Medium scenario to 69% in the High Non-EV Technology Advancement case. The sales are replaced by increases in HEV and conventional sales. In the Low Oil Price scenario, PEV sales share also reaches 69% in 2050, with conventional vehicles taking slightly more market share than in the High Non-EV Technology scenario.[88] These sensitivity results indicate that even if conventional vehicle technology

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[87] BEV-100 represents a BEV with a 100-mile range. Similarly, PHEV-25 represents a PHEV with a 25-mile all-electric range.

[88] Conventional vehicles make up 14%, 16%, and 17% of 2050 sales in the Medium Electrification, High Non-EV Technology Advancement, and Low Oil Price scenarios, respectively.

advances in line with PEV-specific technology, and with a lower price difference between gasoline and electricity, PEVs still reach high sale levels in these ADOPT scenarios, which rely on the Rapid technology advancement case for battery costs (see Jadun et al. 2017).

The ADOPT results presented here are directly used for the Medium scenario, but we also use ADOPT, to a lesser degree, to inform the High scenario. To develop the High scenario, we adjust the ADOPT inputs shown in Table B. to instead use the Rapid advancement trajectory in Jadun et al. 2017 for battery costs (ADOPT results shown Figure B.4). The sales shares from 2015 to 2033 are taken from ADOPT, but we extrapolate the results to 2050 to represent higher levels of electrification.[89] We assume the internal combustion engine vehicle and HEV market share will transition to PHEVs, and the PHEV market share will transition to long range BEVs, resulting in 100% PEV penetration for light-duty cars and 91% PEV penetration for light-duty trucks.

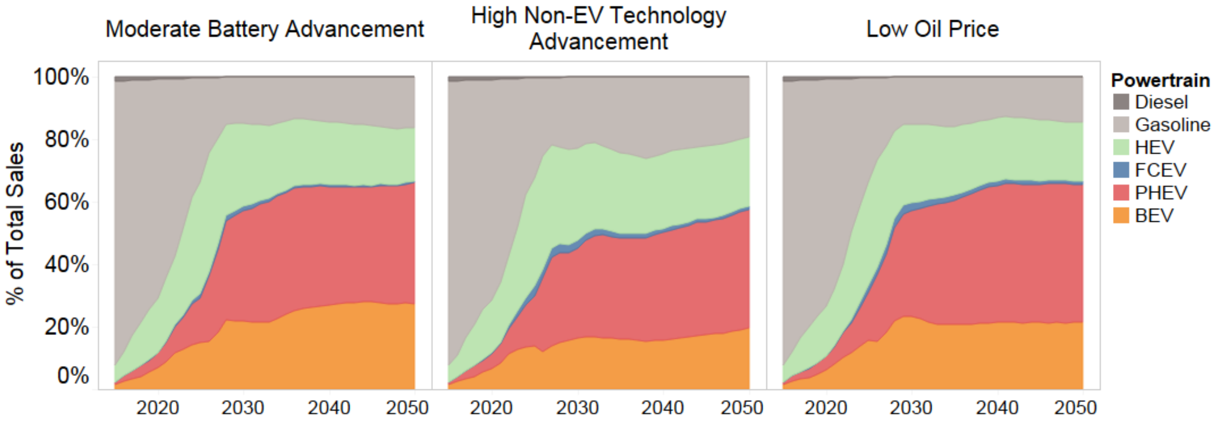

Figure B.6. Sensitivity of vehicle sales (top) and sales shares (bottom) to modeling assumptions

All scenarios use the Moderate Battery Advancement projection.

Results from a validated consumer choice model such as ADOPT indicate that significant electrification is possible in the light-duty transportation sector under the assumptions considered for the Medium scenarios (see Table B.1). Within the model, electric vehicle technologies have economic (fuel cost savings), non-economic (acceleration), and policy-related (CAFE) advantages over conventional vehicles which leads to increased sales, despite potential disadvantages resulting from limited range and related range anxiety, fueling infrastructure limitations (in terms of recharging time and infrastructure availability), and other consumer preferences and tradeoffs. The analysis presented here demonstrates that PEV, especially BEV, adoption is highly sensitive to future battery advancements. For the EFS scenarios, which are designed to examine the impacts of increased electrification in the U.S. energy system, we rely on the ADOPT projections that utilize more-optimistic battery technology assumptions which is consistent with a future with widespread electrification in transportation. Specifically, the sales share percentages obtained from ADOPT, and presented in this Appendix, feed into the EnergyPATHWAYS framework for LDVs in the Medium scenario only.

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[89] The High electrification scenario is meant to explore “what-if” scenarios, such as disruptive technologies, which are included in the current ADOPT framework.

B.2 Medium-Duty and Heavy-Duty Vehicle Adoption

Because of model and data limitations, we base the EFS MDV and HDV adoption scenarios on expert judgment rather than rely on consumer choice. In the Reference scenario, we assume negligible electrification in the medium- and heavy-duty subsectors. In the Medium scenario, which reflects a future with widespread yet plausible electrification, we assume adoption of electric technologies in the medium- and heavy-duty subsectors primarily occurs for applications with shorter driving ranges and lower power requirements. In the High electrification scenario, which includes technological breakthroughs and increased support for electrification, we assume electrification in these subsectors is possible for longer-range applications as well. For example, advances in dynamic charging (e.g., catenary) could facilitate electrification of long-haul HDVs.

To develop the electric technology adoption levels for MDVs and HDVs, we rely on the 2002 Vehicle Inventory and Use Survey (VIUS),[90] which provides data on physical and operational characteristics of the national truck fleet (DOC n.d.). The VIUS data set includes the annual mileage traveled by trucks for various operating ranges (Figure B.7), which serves as a proxy for vehicle applications in this analysis. The majority (63%) of miles traveled by MDVs is made up of trucks with operating ranges less than 50 miles, with minimal miles occurring in operating ranges greater than 500 miles. In contrast, only 24% of miles traveled by HDVs occurs in operating ranges less than 50 miles, while 31% occurs in operating ranges over 500 miles. We assume electrification is more feasible in the medium-duty subsector because of the shorter driving distances, and that significant adoption of electric technologies in the longer-range heavy-duty subsector requires technological breakthroughs envisioned in the High scenario.

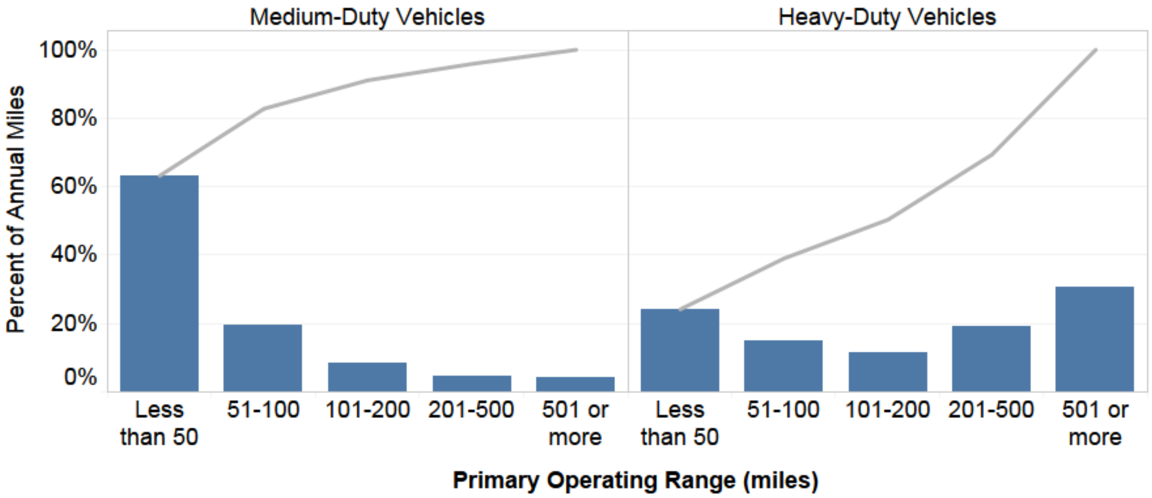

Figure B.7. Percentage of total annual miles (bars) and cumulative percent of total (line) by primary operating range for MDVs (left) and HDVs (right)

Data are from DOC (n.d.).

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[90] VIUS is the most comprehensive data set available on truck fleet characteristics, but it was last conduced in 2002. Given this, the data presented here may not completely reflect today's truck fleet.

The 2050 adoption levels for medium- and heavy-duty vehicles reflect the assumptions described above. Table B.2 shows the assumed share of mileage within each vehicle operating range electrified by 2050 in the Medium and High scenarios. In the Medium scenario, electrification occurs only in operating ranges under 200 miles, which results in shares of electric technologies of 29% and 10% for MDVs and HDVs, respectively. Shares increase to 61% for MDVs and 41% for HDVs in the High electrification scenario, enabled by improved battery technology and dynamic charging for long-haul vehicles.

Table B.2. Medium- and Heavy-Duty Electrification Shares in 2050 by Primary Operating Range for Medium and High Scenarios

Subsector	EFS Scenario	Share of VMT Electrified in Primary Operating Range					Total Share of VMT Electrified
		Less than 50 miles	51–100 miles	101–200 miles	201–500 miles	Over 500 miles	
MDVs	Medium	40%	20%	10%	0%	0%	29%
	High	80%	50%	20%	10%	0%	61%
HDVs	Medium	30%	15%	5%	0%	0%	10%
	High	80%	50%	40%	30%	15%	41%

As with MDVs and HDVs, we exogenously defined sales shares for electric transit buses rather than basing those shares on outcomes from consumer choice models. We only considered electrification of buses providing local transit services; we did not consider electric bus adoption for long-distance applications. (No distance-based considerations were used in the development of the bus sales shares.) Battery electric bus sales shares in 2050 were assumed to reach 1%, 50%, and 100% in the Reference, Medium, and High scenarios, respectively.

Appendix C. Buildings Technology Adoption

Appendix Author: Daniel Steinberg (NREL)

Development of the EFS Reference, Medium, and High electrification scenarios for the residential and commercial buildings subsectors is based on a combination of analysis and extension of existing trends, expert judgment, and literature review. Ultimately, the extent of the adoption of electric buildings technologies will depend on a range of factors including future technology cost and performance, policy support, the evolution of electricity prices, consumer preferences (e.g., for integrated building control systems), and additional non-economic influences (e.g., brand loyalty and environmental motivation). In this appendix, we detail the development of the adoption scenarios for heat pumps for space heating applications.

Air sources heat pumps (ASHPs) have been a viable alternative or complementary technology to conventional fossil-fueled heating systems since the 1960s. The rate of adoption of heat pumps has varied over the past five decades and has been driven by a range of factors, including the relative differences in electricity and natural gas prices, shifts in population patterns and housing characteristics, economic growth, and regulatory actions (Lapsa et al. 2017), but it has generally increased as ASHPs have increased in efficiency and decreased in cost (DOE 2016).

Electric ASHPs provided the primary source of heating for approximately 10% of residential buildings in 2015 and 9% of total commercial floor space in 2009 in the United States (RECS 2015; CBECS 2012). However, adoption of ASHPs is not uniform across the country (see Figure C.1). Of the 12.1 million homes and 11.8 billion square feet of commercial floor space that used ASHPs as a primary heating source, 90% of residential and 80% of commercial ASHPs were in moderate or warm climates (RECS 2015; CBECS 2012).[91] The preference for ASHPs in moderate or warm climates is driven by the fact that heat pumps can provide both heating and cooling services—obviating the need for both a heating technology (gas furnace) and a cooling technology (air conditioner)—and because the efficiency of heat pumps (operating in heating mode) is relatively high in milder winters. Despite this, adoption in cold climate regions is rapidly increasing due to both successful research and development efforts to increase the efficiency of ASHPs in cold climates and efforts to reduce barriers to adoption through deployment programs and incentives (Baxter and Groll 2017a; NEEP 2017b). From 2005 to 2015, the percentage of residences that used electric ASHPs as their primary heating source in cold and very cold climates increased from just under approximately 1.6% to 3.1%; although shares remain low, this represents almost a 200% increase in overall stock share over 10 years, or annual growth of close to 7% (RECS 2005, 2015).

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[91] We define “moderate or warm” climates as all regions outside the *Cold* or *Very Cold* Building America climate regions, which include the *Mixed-humid, Mixed-dry, Hot-dry, Hot-humid,* and *Marine* climate regions (Baechler et al. 2015).

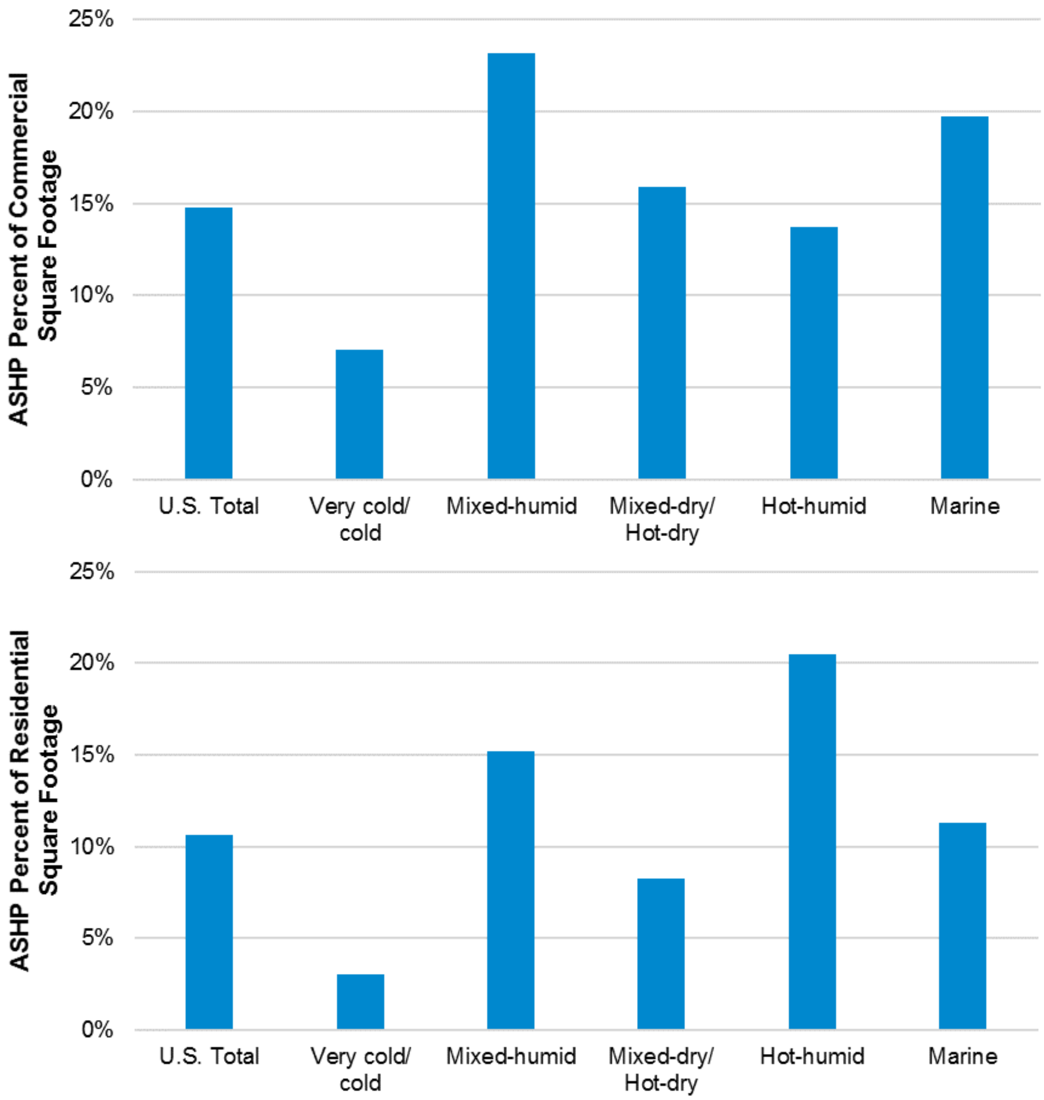

Figure C.1. Existing stock of heat pumps for space heating in residential homes in 2015 (top) and commercial buildings in 2012 (bottom)

As a result of the current trends of increasing adoption of ASHPs, our Reference case assumes sales share of ASHPs for space conditioning continues to increase across all regions, but at relatively slow rates, such that by 2050 the residential sales share in moderate or warm climates reaches approximately 20% (with greater adoption in warm regions than moderate regions). Commercial adoption is also expected to increase, but sales share achieved are lower overall than they are in the residential sector. Sales shares of ASHPs in moderate or warm climates are assumed to reach just under 12%.

As described above, the Medium and High adoption scenarios are qualitatively defined as scenarios that reflect more favorable conditions for research and development, deployment, and adoption of these technologies. The Medium scenario reflects a future with widespread electrification that is plausible, but not transformational, and the High scenario reflects a future under which end-use trends are dramatically altered through research and development and various forms of support for electric technology adoption. For ASHPs, these scenarios are represented by assuming substantial growth in the sales share of ASHPs across all regions. Under the Medium case, sales shares in moderate or warm climates reach 86% and 45% by 2050 in the residential and commercial sectors, respectively. In cold climates (using the New England census division as a proxy), sales shares reach 42% and 17%—which is substantially below the assumed shares in moderate or warm climates. Under the High scenario, we assume significant breakthroughs in cold climate heat pumps drive sales share increases to 50% (residential) and 30% (commercial) by 2050 in cold climates and begin to drive penetration in very cold climates, with shares increasing to 10% in the residential sector. In moderate or warm climates, sales share of ASHPs begin to approach 100% by 2050.

Appendix D. Industry Adoption Heuristic

Appendix Author: Colin McMillan (NREL)

We assume industrial end uses experience many barriers to electrification that are associated with industrial firms' capital investment processes, including the desire to maintain profitability and avoid disruption to production processes. Ideally, we would base our adoption scenarios on a model of firm behavior that included the relative costs and productivity benefits of fuel-fired equipment and electrotechnologies. Because of a lack of relevant publicly available data and a lack of existing adoption models for industrial firms, however, we developed an industrial adoption heuristic to capture the relative attractiveness of our representative electrotechnologies. An additional factor for the decision to use an adoption heuristic is the inconclusive results of analyzing Industrial Assessment Center data on electrotechnology payback and adoption (Jadun et al. 2017). New research on industrial electrotechnology adoption—particularly research that quantifies associated benefits to industrial productivity and other non-energy benefits—is needed.

We model industrial adoption using a logistic functional form, as we describe in Section 4. The adoption heuristic is based on our subjective ranking of typical productivity benefits provided by industrial electrotechnologies. Our decision to define industrial adoption in terms of productivity benefits is grounded in the literature on technology adoption in industry. In this appendix, we briefly summarize several sources from the literature and describe our adoption heuristic. Our approach to industrial electrotechnology adoption uses three adoption categories that do not distinguish between specific technologies, end uses, or industries.

A seminal study that examined the adoption of twelve new industrial technologies by firms in four industries found the rate of firm imitation varied widely, with the time required for half of all firms to adopt a technology ranging from 0.9 years to 15 years (Mansfield 1961). A deterministic model was developed to explain the proportion of firms not adopting a technology over time as a function of the proportion of firms already adopting the technology, the profitability of adopting the technology, and the size of investment required for adopting the technology. The study found that technology adoption could be approximated by a logistic curve, and it found evidence of higher imitation rates for technologies that were more profitable and required smaller investment.

The adoption heuristic assumes that opportunities to electrify end uses that do not have characteristics that improve industrial productivity (e.g., increased production rates and improved product quality) are much less likely to be implemented, even under a high electrification scenario. This assumption is based on historical (c.f. Mansfield 1961) and anecdotal evidence of the importance of productivity and other non-energy benefits. Additionally, we note that energy-intensive industries—such as steel, cement, chemicals, and pulp and paper—face particular barriers to innovation in general that result from their industry and market structures, high capital intensity and long investment cycles, and focus on incremental technology improvements, among other factors (Wesseling et al. 2017).

Under our adoption heuristic, heat pumps for space conditioning[92] and electric boilers are assumed to have little, if any, characteristics that increase industrial productivity.[93] Technology characteristics that directly benefit production are also assumed to be a proxy for the profitability of electrotechnology adoption. One of three adoption trajectories is selected for each relevant industry and end use for the Medium and High electrification scenarios. We do not distinguish between industries or end uses; an adoption trajectory is assigned only to an electrotechnology based on our assumptions of its productivity benefits. Note also that electrification of industry occurs at the end-use level with the substitution of electricity for existing combustion fuels and not at the level of individual technologies or processes. An induction furnace and an infrared heater are assumed to follow the same adoption pathway for process heating regardless of industry, for example. These trajectories are shown in Table D.1. Note that these values represent the fraction of new capacity that is electrified in each year. For example, electrotechnologies that provide limited or no benefit to industrial productivity are assumed to not be adopted under the moderate scenario and begin adoption in 2040 at 5% of new capacity additions under the high scenario.

We do not make any assumptions about the adoption of industrial energy efficiency measures. We discuss our assumptions regarding the use of technology possibility curves (TPCs) to represent technological advancement of electrotechnologies in Text Box 7.1.

Table D.1. Industry Electrotechnology Adoption Heuristics

	Moderate				High			
	2020	2030	2040	2050	2020	2030	2040	2050
No or Limited Productivity Benefits	0	0	0	0	0	0	5%	10%
Moderate Productivity Benefits	0	0	5%	10%	1%	10%	20%	25%
Large Productivity Benefits	1%	10%	20%	25%	5%	25%	60%	75%

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[92] Heat pump adoption for industrial HVAC is linked to air source heat pump adoption in commercial buildings.

[93] Electric boilers could have local air quality and environmental permitting benefits, but these are assumed to be secondary to improvements to production or product quality.

Appendix E. EnergyPATHWAYS Data Sources

Appendix Authors: Ryan Jones and Ben Haley (Evolved Energy Research)

The demand-side of EnergyPATHWAYS (EP) projects future energy, stock, and sales using one of several methods that depend on the availability of input data. Each of the calculation methods is briefly explained in Table E.1, and Tables E.2–E.10 explain the basic inputs and data sources.

Table E.1. EnergyPATHWAYS Terminology

Column Name	Explanation
Subsector	A subsector is the basic organizing unit within the demand-side of EnergyPATHWAYS. One subsector may depend on another (e.g., clothes washing efficiency impacts hot water demand), but each subsector has a distinct type of service demand.
Unit	Input unit for energy, stock, or service demand.
Service Demand Dependent	If stock is service-demand dependent, it means service demand is calculated first through 2050 and is then used as a driver to project the size of the total stock.
Stock Dependent	If service demand is stock dependent, it means the size of the total stock is calculated first through 2050 and then is used as a driver to project service demand.
Driver	Drivers are data that extend through 2050 that are used to extrapolate a data input available only for a subset of years. Typically, a data input is first divided by a driver to create a ratio of data to driver; this ratio is then extrapolated using one of many regression techniques, although it is also frequently just held constant across all years. The ratio available for all years is then multiplied back by the driver to arrive at the final data time-series. Drivers may themselves have other drivers; for instance, population drives households and households drive residential square footage.
Input Data Geography	The native input geography for the data; all data go into the model in its native geography and are mapped to the primary geography (state) within each subsector.
Downscaling Method	Each downscaling method or mapping key is used to change the geography of a data input by creating part-to-whole factors that can apportion data from census to state, for instance. Most downscaling data come from geographic information system data sets and is input to EnergyPATHWAYS on a county level.
Input Data Year(s)	The years for which data are natively available; when data are not available through 2050, drivers and regression techniques are used for extrapolation.
Source	Source of data input.

Approach 1: Stock and Service Demand

When provided with both stock and service demand data, the model uses a stock rollover approach to calculate the share of service demand satisfied by each technology and vintage. This allows us to calculate overall energy demand based on vintage technology characteristics.

Table E.2. Stock Data

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Residential Lighting	bulbs per housing unit	no	total square footage	United States	households in 2010	2012	AEO2017
Residential Clothes Washing	clothes washer	no	households	census division	households in 2010	2009	RECS 2009
Residential Clothes Drying	clothes dryer	no	households	census division	households in 2010	2009	RECS 2009
Residential Dishwashing	dishwashers per household	no	households	census division	households in 2010	2009	RECS 2009
Residential Refrigeration	cubic feet	no	households	census division	households in 2010	2009	RECS 2009
Residential Freezing	cubic feet	no	households	census division	households in 2010	2009	RECS 2009
Commercial Water Heating	capacity factor	no	commercial square footage	census division	households in 2010	2012	AEO2017
Commercial Space Heating	capacity factor	no	commercial square footage	census division	HDD x commercial square footage	2012–2013	AEO2017
Commercial Air Conditioning	capacity factor	no	commercial square footage	census division	households in 2010	2012	AEO2017
Commercial Lighting	capacity factor	no	n/a	census division	households in 2010	2012	AEO2017
Commercial Refrigeration	capacity factor	no	commercial square footage	census division	households in 2010	2012	AEO2017
Commercial Cooking	capacity factor	no	commercial square footage	census division	households in 2010	2012	AEO2017

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Commercial Ventilation	capacity factor	no	commercial square footage	census division	households in 2010	2012	AEO2017
Light-Duty Cars	car per mile traveled	yes	n/a	United States	service demand	2012, 2020, 2030, 2040	AEO-2015
Light-Duty Trucks	truck per mile traveled	yes	n/a	United States	service demand	2012, 2020, 2030, 2040	AEO-2015
Medium-Duty Trucks	truck	yes	n/a	United States	service demand	2015	AEO2015
Heavy-Duty Trucks	truck	yes	n/a	United States	service demand	2011	AEO2015
Transit Buses	bus	yes	n/a	United States	service demand	2014	APTA 2017

Table E.3. Service Demand Data

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Residential Lighting	kilolumen-hr per housing unit	no	total square footage	United States	households in 2010	2012	
Residential Clothes Washing	Csde218# cubic feet cycle	yes	n/a	census division	stock	2009	derived from RECS 2009
Residential Clothes Drying	pound	yes	n/a	census division	stock	2009	derived from RECS 2009
Residential Dishwashing	cycle	yes	n/a	census division	stock	2009	derived from RECS 2009
Residential Refrigeration	cubic feet	yes	n/a	census division	stock	2009	derived from RECS 2009
Residential Freezing	cubic feet	yes	n/a	census division	stock	2009	derived from RECS 2009
Commercial Water Heating	TBtu	no	commercial square footage	census division	employment in all industries (NAICS, no code) 2007	2012–2050	AEO2017
Commercial Space Heating	TBtu	no	commercial square footage	census division	HDD x commercial square footage	2012–2050	AEO2017
Commercial Air Conditioning	TBtu	no	commercial square footage	census division	CDD x commercial square footage	2012–2050	AEO2017
Commercial Lighting	gigalumen-year	no	commercial square footage	census division	employment in all industries (NAICS, no code), 2007	2012–2050	AEO2017
Commercial Refrigeration	TBtu	no	commercial square footage	census division	employment in all industries (NAICS, no code), 2007	2012–2050	AEO2017
Commercial Cooking	TBtu	no	commercial square footage	census division	employment in all industries (NAICS, no code), 2007	2012–2050	AEO2017
Commercial Ventilation	gigacubic_foot	no	commercial square footage	census division	employment in all industries (NAICS, no code), 2007	2012–2050	AEO2017

Subsector	Unit	Stock Dependent	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Light-Duty Cars	gigamile	no	MD + HD VMT historical	United States	LDV VMT share	2007, 2015–2050	AEO2017
Light-Duty Trucks	gigamile	no	MD + HD VMT historical	United States	LDV VMT share	2012–2050	AEO2017
Medium-Duty Trucks	mile	no	gasoline sales volumes	United States	MDV VMT share	2015–2050	AEO2017
Heavy-Duty Trucks	mile	no	gasoline sales volumes	United States	HDV VMT share	2015–2050	AEO2017
Transit Buses	mile	no	population	census division	square footage	1995–2008	APTA 2017

Approach 2: Stock and Energy Demand

When provided with both stock and energy demand data, the model must first derive an estimate of service demand. This is done for years in which both energy demand and stock are input. Using a stock rollover approach, we can calculate the average efficiency of the stock in the years that we have energy demand. This allows us to derive an estimate of energy service demand that we can project forward. After this step, the approach is the same as the one utilized for subsectors where we enter service demand directly.

Table E.4. Stock Data

Subsector	Unit	Service Demand Dependent	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Residential Water Heating	water heater	no	households	census division	households in 2010	2009	RECS 2009
Residential Space Heating	space heater	no	households	census division	households in 2010	2009–2015	AEO2017
Residential Air Conditioning	air conditioner	no	households	census division	households in 2010	2009	RECS 2009
Residential Cooking	cooktop	no	households	census division	households in 2010	2009	RECS 2009
Industrial Boilers	capacity factor	yes	n/a	United States	service demand	2015	NREL
Industrial Process Heat	capacity factor	yes	n/a	United States	service demand	2015	NREL
Industrial Space Heating	capacity factor	yes	n/a	United States	service demand	2015	NREL
Industrial Machine Drives	capacity factor	yes	n/a	United States	service demand	2015	NREL
Industrial Curing	capacity factor	no	n/a	United States	service demand	2015	NREL
Industrial Drying	capacity factor	no	n/a	United States	service demand	2015	NREL

Table E.5. Energy Demand Data

Subsector	Unit	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Residential Water Heating	MMBtu	households	census division	households in 2010	2009	RECS 2009
Residential Space Heating	MMBtu	HDD; occupied square footage	census division	heating degree days x residential square footage	2009–2015	AEO2017
Residential Air Conditioning	MMBtu	CDD	census division	cooling degree days x residential square footage	2009	RECS 2009
Residential Cooking	MMBtu	households	census division	households in 2010	2009	RECS 2009
Industrial Boilers	U.S. dollars (USD)	value of shipments	census region	earnings in manufacturing (NAICS 31-33), 2007	2011–2050	AEO2017
Industrial Process Heat	USD	value of shipments	census region	earnings in manufacturing (NAICS 31-33), 2007	2011–2050	AEO2017
Industrial Space Heating	USD	value of shipments	census region	earnings in manufacturing (NAICS 31-33), 2007	2011–2050	AEO2017
Industrial Machine Drives	USD	value of shipments	census region	earnings in manufacturing (NAICS 31-33), 2007	2011–2050	AEO2017
Industrial Curing	USD	value of shipments	census region	earnings in manufacturing (NAICS 31-33), 2007	2011–2050	AEO2017
Industrial Drying	USD	value of shipments	census region	earnings in manufacturing (NAICS 31-33), 2007	2011–2050	AEO2017

Approach 3: Energy Demand Only

In subsectors where we only have energy demand, we downscale and utilize underlying drivers of that energy demand, along with regression techniques, to project the demand to 2050. These are primarily from sources that project to 2050 themselves.

Table E.6. Other Data

Subsector	Unit	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Residential computers and related	MMBtu	households	census division	households in 2010	2009–2050	AEO2017
Residential televisions and related	MMBtu	households	census division	households in 2010	2009–2050	AEO2017
Residential Secondary Heating	MMBtu per household	households; HDD	census division	households in 2010	2009	RECS 2009
Residential other uses	MMBtu	households	census division	households in 2010	2009—-2050	AEO2017
Residential Furnace Fans	MMBtu	households	census division	households in 2010	2009	RECS 2009
Office Equipment (P.C.)	quads	office space	United States	employment in all industries (NAICS, no code) 2007	2015–2050	AEO2017
Office Equipment (Non-P.C.)	quads	office space	United States	employment in all industries (NAICS, no code) 2007	2015–2050	AEO2017
Commercial Other	quads	comm square footage	United States	employment in all industries (NAICS, no code) 2007	2015–2050	AEO2017
Non-Combined Heat and Power District Services	kBtu per square foot	commercial square footage	census division	households in 2010	2012	CBECS 2012
Combined Heat and Power District Services	TBtu	commercial square footage	United States	households in 2010	2015–2050	AEO2017
Domestic Shipping	TBtu	n/a	United States	marine fuel use	2015–2050	AEO2017
Military Use	TBtu	n/a	United States	households in 2010	2015–2050	AEO2017
Motorcycles	TBtu	population	United States	households in 2010	2012–2050	AEO2017
Lubricants	TBtu	population	United States	households in 2010	2015–2050	AEO2017
International Shipping	TBtu	n/a	United States	Marine Fuel Use	2015–2050	AEO2017

Subsector	Unit	Driver	Input Data: Geography	Downscaling Method	Input Data: Year(s)	Source
Recreational Boats	TBtu	n/a	United States	households in 2010	2015–2050	AEO2017
School and intercity buses	TBtu	passenger miles, population	United States	buses VMT share	2015–2050	AEO2017
Passenger rail	TBtu	rail passenger miles	census division	rail fuel use	2015–2050	AEO2017
Freight rail	TBtu	gigaton mile service demand	census division	rail fuel use	2015–2050	AEO2017
Aviation	TBtu	seat miles, population	United States	aviation fuel use	2015–2050	AEO2017
Various Industrial Subsectors[a]	TBtu	subsector value of output	census region	value of shipments	2011–2050	AEO2017

[a] Includes agriculture—crops; agriculture—other; metal and other non-metallic mining; construction; food and kindred products; paper and allied products; bulk chemicals; glass and glass products; cement; iron and steel; aluminum industry; fabricated metal products; machinery; computer and electric products; transportation equipment; electric equipment, appliances and components; wood products; plastic and rubber products; and balance of manufacturing other.

Demand Technology Cost and Performance Sources

Tables E.7–E.10 show the sources for technology cost and performance trajectories. In cases where the underlying data was not available to 2050, costs and performance are held constant after the last year provided. Linear interpolation is used to fill intermediate years when data was not reported on an annual basis.

Table E.7. Residential and Commercial Buildings

Subsector	Technologies	Source
Residential Space Heating and Air Conditioning	air source heat pump (ASHP), ducted	Jadun et al. 2017
	ductless mini-split heat pump	Dentz, Podorson, and Varshney 2014
	remainder	EIA 2015
Residential Water Heating	heat pump water heater	Jadun et al. 2017
	remainder	EIA 2015
Residential Remaining Subsectors	all	EIA 2015
Commercial Space Heating and Air Conditioning	ASHP	Jadun et al. 2017
	remainder	EIA 2015
Commercial Water Heating	heat pump water heater	Jadun et al. 2017
	remainder	EIA 2015
Commercial Lighting	all	EIA 2017c
Commercial Building Shell	all	EIA 2017c
Commercial Remaining Subsectors	all	EIA 2015

Table E.8. Transportation Data Sources

Subsector	Technologies	Source
Light-duty Vehicles	battery electric vehicle and plug-in hybrid electric vehicle	Jadun et al. 2017
	hydrogen fuel cell vehicle	NRC 2013
	remainder	Efficiency: EIA 2015 Cost: NRC 2013
Medium-Duty Vehicles	battery electric	Jadun et al. 2017
	hydrogen fuel cell	NRC 2013
	remainder (e.g., compressed natural gas and diesel)	NPC 2012
Heavy-Duty Vehicles	battery electric	Jadun et al. 2017
	hydrogen fuel cell	Fulton and Miller 2015
	reference diesel, gasoline and propane	Efficiency: AEO2015 Cost: NPC 2012
	diesel hybrid and liquefied pipeline gas	NPC 2012
Transit Buses	all	Jadun et al. 2017; ADOPT model

Table E.9. Industry Data Sources

Subsector	Technologies	Source
Industrial Space Heating	ASHP	Jadun et al. 2017
	furnace	EIA 2015
Industrial Boilers	all	Jadun et al. 2017
Industrial Process Heat	all	Jadun et al. 2017
Industrial Curing	all	Jadun et al. 2017
Industrial Drying	all	Jadun et al. 2017
Industrial Machine Drives	all	Jadun et al. 2017

Table E.10. Unitized End-Use Load Shapes

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
Bulk System Load	initial electricity reconciliation, all subsectors not otherwise given a shape	Emissions and Generation Resource Integrated Database (EGRID) with additional granularity in the western interconnection	hourly, 2012	FERC Form No. 714
Light-Duty Vehicles (LDVs)	all LDVs	United States	month-hour-weekday/weekend average, separated by home vs. work charging	Evolved Energy Research analysis of 2016 National Household Travel Survey
Water Heating (Gas Shape)[a]	residential hot water		month-hour-weekday/weekend average	Northwest Energy Efficiency Alliance Residential Building Stock Assessment Metering Study (Northwest)
Other Appliances	residential TV & computers			
Lighting	residential lighting			
Clothes Washing	residential clothes washing			
Clothes Drying	residential clothes drying			
Dishwashing	residential dish washing			
Residential Refrigeration	residential refrigeration			
Residential Freezing	residential freezing			
Residential Cooking	residential cooking			
Industrial Other	all other industrial loads			California Load Research Data
Agriculture	industry agriculture			
Commercial Cooking	commercial cooking			
Commercial Water Heating	commercial water heating	North American Electric Reliability Corporation (NERC) region		EPRI Load Shape Library 5.0
Commercial Lighting Internal	commercial lighting			
Commercial Refrigeration	commercial refrigeration			

Shape Name	Used By	Input Data Geography	Input Temporal Resolution	Source
Commercial Ventilation	commercial ventilation			
Commercial Office Equipment	commercial office equipment			
Industrial Machine Drives	machine drives			
Industrial Process Heating	process heating			
electric_furnace_res	electric resistance heating technologies	IECC Climate Zone by state (114 total geographical regions)	hourly, 2012 weather	Evolved Energy Research Regressions trained on NREL building simulations in select U.S. cities for a typical meteorological year and then run on county level HDD and CDD for 2012 from the National Oceanic and Atmospheric Administration (NOAA)
reference_central_ac_res	central air conditioning technologies			
high_efficiency_central_ac_res	high-efficiency central air conditioning technologies			
reference_room_ac_res	room air conditioning technologies			
high_efficiency_room_ac_res	high-efficiency room air conditioning technologies			
reference_heat_pump_heating_res	ASHPs			
high_efficiency_heat_pump_heating_res	high-efficiency ASHPs			
reference_heat_pump_cooling_res	ASHP s			
high_efficiency_heat_pump_cooling_res	high-efficiency ASHPs			
chiller_com	commercial chiller technologies			
dx_ac_com	direct expansion air conditioning technologies			
boiler_com	commercial boiler technologies			
furnace_com	commercial electric furnaces			
Flat shape	MDV and HDV charging	United States	n/a	n/a

[a] natural gas shape is used as a proxy for the service demand shape for electric hot water due to the lack of electric water heater data.

Appendix F. Bounding Scenarios

Appendix Authors: Ryan Jones (Evolved Energy Research) and Trieu Mai (NREL)

In addition to the core—Reference, Medium, and High—electrification scenarios presented in the main body of this report, we also modeled two bounding scenarios of electricity consumption. On the low end, we include a scenario where electricity demand remains flat over time as a result of increased adoption of energy efficiency measures combined with a lack of incremental electrification (beyond that from the Reference case). Creation of the low electricity growth scenario relies on adoption of high-efficiency technologies (e.g., new residential air conditioners sales become 100% "high efficiency" by 2035) at a pace and scale informed by prior study (Williams et al. 2014). In the low growth scenario, 2050 electricity final energy demand is 18% below that in the reference scenario with identical energy services provided.

On the high end, we model a scenario where electric technology adoption occurs immediately and fully starting in 2018; however, equipment stock turnover is slowed by equipment lifetimes, some of which persist through multiple decades, and electrification only occurs for those end uses modeled in our core scenarios. Within a narrow sense, this scenario reflects a technical potential for electrification.

These two bounding scenarios can be used to further contextualize the core EFS scenarios and can be used for future analysis of more-extreme cases than what we detail in the main report. The full data from these scenarios are available for such analysis. Below, we present the high-level results from these two scenarios. Figure F.1 compares the annual electricity consumption results in these two scenarios with those from the Reference scenario. Table F.1summarizes 2050 consumption and electricity share of final energy by sector.

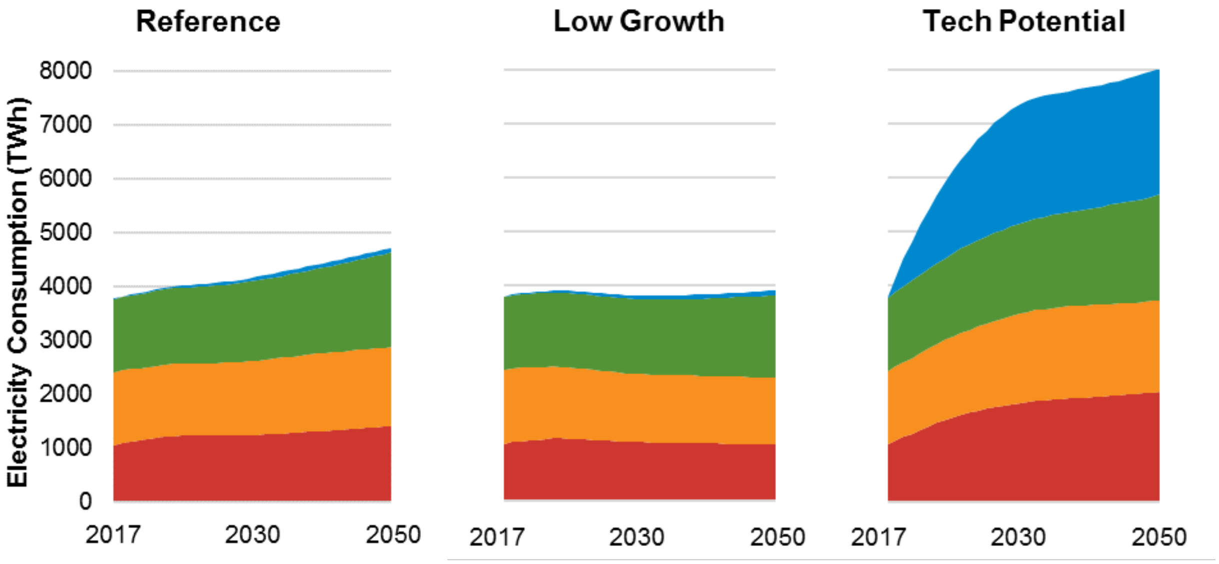

Figure F.1. Annual U.S. electricity consumption in the Reference and bounding scenarios

Moderate technology advancement projections are shown.

Table F.1 Electricity Consumption and Share of Final Energy by Sector and Scenario

Annual Electricity Consumption (TWh)		**2050 Reference**			**2050 Low Growth**			**2050 Technical Potential**		
	2016	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**
Transport	7.5	78	88	101	78	88	101	2,129	2,344	2,638
Residential	1,418	1,462	1,474	1,503	1,216	1,241	1,295	1,625	1,689	1,793
Commercial	1,379	1,751	1,755	1,762	1,530	1,532	1,536	1,933	1,965	2,020
Industrial	1,084	1,405	1,405	1,406	1,050	1,050	1,051	2,035	2,038	2,044
Total	**3,889**	**4,696**	**4,722**	**4,772**	**3,874**	**3,911**	**3,983**	**7,722**	**8,037**	**8,494**
% of Final Energy		**2050 Reference**			**2050 Low Growth**			**2050 Technical Potential**		
	2016	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**	**Rapid**	**Moderate**	**Slow**
Transport	0	1	1	1	1	1	1	57	59	62
Residential	45	44	45	45	43	43	44	85	86	86
Commercial	53	62	62	62	60	60	60	86	86	87
Industrial (excluding refining)	15	23	23	23	21	21	21	40	40	40
Total	**19**	**23**	**23**	**23**	**21**	**21**	**22**	**60**	**61**	**62**

Historical (2016) data from EIA monthly energy review (EIA n.d.). Attribution to each sector is based directly from EIA, which may include behind-the-meter PEV charging in the residential and commercial sectors. Historical 2016 data presented here differ slightly from modeled 2016 values from EP. Data also include net self-generation of electricity from renewable sources (except geothermal) and combustible fuels. The consumption data include EIA estimates of behind-the-meter solar generation based on estimated growth rates from the AEO. The electricity consumption estimates include electricity used for fossil fuel extraction and refining; however, estimated final energy shares from electricity do not include these uses.

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