ELECTRIC POWER
RESEARCH INSTITUTE

U.S. National Electrification Assessment

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3. Modeling Insights from the USNEA

FOREWORD

Over the past few years, the Electric Power Research Institute (EPRI) has collaborated with many stakeholders to examine the forces that are transforming the world's energy systems. At the center of this work is our concept of an Integrated Energy Network (IEN)*—the idea that the effective integration of energy supplier and user networks can and will lead to more reliable, flexible, and affordable energy services (*www.ien.epri.com*).*

In this paper we highlight a key element of the IEN: the critical and growing role that electricity will play in the future energy system. Many others have envisioned a more electric future. EPRI offers a new systematic look, anchored in leading-edge modeling, to understand key drivers, potential barriers, and the possible pace of electrification from many distinct viewpoints: customers, power generation and delivery, and equipment providers, as well as the impact on the environment and the economy. The EPRI modeling approach differs from other studies in many respects—including our representation of economic trade-offs, integration of electric demand and supply, and outlook on the rate of technological change, particularly for energy efficiency, where our view is informed by years of extensive laboratory testing and field demonstration projects.

Electricity's role in the energy system has grown for over a century, and it is poised to continue growing steadily or perhaps accelerate, while improving our standard of living. Rapid technological change, such as improvements in energy storage and pervasive digitalization, dramatically expand the range of electric technologies that make economic sense—providing superior service at a lower cost. Increasingly cleaner electric generation combines with a desire for a cleaner environment and healthier workplaces to potentially accelerate this change and create an ever cleaner and more efficient global energy system.

EPRI's Board of Directors approved an Electrification Initiative in 2017 to study the pivotal role of efficient electrification, including analysis, creation of an electrification technology pipeline, and expansion of R&D collaborations. This document, the U.S. National Electrification Assessment (USNEA), frames the discussion, but it's just the start. We will initiate U.S. state-level studies starting in 2018 to explore the local opportunities and realities; collaborate with member companies and others to gain a richer understanding of efficient electrification outside the United States; continue to accelerate the development of advanced electric technologies and the infrastructure needed to incorporate them to meet customer desire and need; and expand collaborations with other stakeholders at the international, national, state, and local levels, who are focused on understanding electrification opportunities and challenges.

We offer this document to spark discussion of efficient electrification. We invite you to visit our electrification website *where you can subscribe to our monthly* electrification newsletter *and register to participate in our inaugural* Electrification 2018 conference*, August 20–23, 2018, in Long Beach, California.*

Michael W. Howard, Ph.D., P.E.

President and CEO
Electric Power Research Institute

EXECUTIVE SUMMARY

Electrification describes the adoption of electric end-use technologies. In developing countries, this often refers to making electric power available to customers for the first time. The value of this type of electrification is well established. In more advanced economies, including the United States, electrification increasingly describes electric end-uses displacing other commercial energy forms or providing new services such as 3-D printing and indoor agriculture. EPRI uses efficient electrification to refer to such opportunities across the economy that yield a range of efficiencies—lower cost, lower energy use, reduced air emissions and water use, improved health and safety for customer's workers coupled with the opportunity for gains in productivity and product quality, and increased grid flexibility and efficiency.

EPRI's Efficient Electrification Initiative explores electrification in the context of the global energy system—analyzing the customer value of advanced, end-use technologies that efficiently amplify benefits of cleaner power generation. Coupling EPRI's modeling capabilities with its extensive research on end-use technologies and grid planning and operations, the initiative is assessing interdependent aspects of electric technologies' adoption, electrification's potential to enhance control and flexibility, and the impacts on grid operations and planning.

To help frame EPRI's broad undertaking, this report highlights key findings from EPRI's U.S. National Electrification Assessment (USNEA), which examines customer adoption of electric end-use technologies over the next three decades, along with key implications for efficiency, the environment, and the grid. The study finds that, across a range of assumptions, economy-wide electrification leads to a reduction in energy consumption, spurs steady growth in electric load, and reduces greenhouse gas (GHG) emissions—even in scenarios with no assumed climate policy. Advances in both end-use technologies and technological integration reduce costs, drive higher adoption, and amplify customer benefits. In modeling scenarios with a carbon price, the benefits from electrification are more substantial. This study also focuses attention on needed research and development and challenges for future policy and regulatory frameworks that will guide the transition.

ASSESSMENT APPROACH

The U.S. National Electrification Assessment examined four scenarios with EPRI's US-REGEN energy-economy model[1] to consider opportunities, drivers, and challenges for electrification (Figure ES-1). The ***Conservative*** and ***Reference*** scenarios focus on how changes in technology cost and performance affect outcomes. In the ***Reference*** scenario, technology costs and performance improve over time across the economy, in some cases rapidly, based on anticipated technology trends. The ***Conservative*** scenario considers a slower decline in the relative cost of electric vehicles, a key technology for electrification. Two scenarios explore the impact of potential economy-wide carbon policy: the ***Progressive*** scenario in which carbon is valued at \$15/ton CO_2 starting in 2020, and the ***Transformation*** scenario in which the carbon value starts at \$50/ton CO_2 in 2020.[2] In addition, a natural gas price sensitivity analysis examines the potential impact of rising gas costs on efficient electrification.

All of the scenarios use as a starting point, projections from the U.S. Energy Information Administration's Annual Energy Outlook 2017[3] of economic growth, primary fuel prices and service demands (e.g., vehicle miles traveled by region or square feet of commercial buildings that is heated). EPRI technology assumptions are used in examining alternatives for providing these services. State-level policies such as renewable portfolio standards and carbon policies help guide regional technology choices.

This assessment focuses on cost-effective technology choices with and without a carbon price. It does not estimate some of the possible additional benefits of electrification, including improved air quality, enhanced grid flexibility, increased productivity or comfort, or better workplace safety. These will be examined in state-/utility-specific assessments. The assessment does not specifically assume future market transformations or policy and regulatory frameworks that would favor adoption of electrification technologies or spur investment in supporting infrastructure. The assessment also does not model newly emerging applications for electricity (e.g., indoor agriculture and 3-D printing), which offer potential efficiency, productivity, environmental, and other benefits.

CONSERVATIVE	*Slower Technology Change*	• *AEO 2017 growth path for GDP and service demands, and primary fuel prices* • *EPRI assumptions for cost and performance of technologies and energy efficiency over time* • *Existing state-level policies and targets*
REFERENCE	*Reference Technology*	
PROGRESSIVE	*Reference Technology + Moderate Carbon Price*	
TRANSFORMATION	*Reference Technology + Stringent Carbon Price*	

Figure ES-1. Study Scenario Overview

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[1] US-REGEN is an energy-economy model of the United States. It has been employed extensively over the past decade to explore various energy system issues and potential policies. For this study US-REGEN integrated detailed models of consumer choice. Model structure and assumptions can be found in *US-REGEN Model Documentation*, www.epri.com/#/pages/product/3002010956/.

[2] In both the Progressive and Transformation scenarios the carbon price increases at 7% real per year through 2050.

[3] Annual Energy Outlook 2017: with projections to 2050 at www.eia.gov/outlooks/archive/aeo17/.

KEY INSIGHTS

- *Customers increase their reliance on electric end uses*

In the United States, electricity has grown from 3% of final energy in 1950 to approximately 21% today. Across the four scenarios, electricity's role continues to grow, ranging from 32% to 47% of final energy in 2050. In addition to providing an array of benefits to customers, this trend has important implications for how the electric system will evolve.

Without efficient electrification, EPRI projects that electric loads will decline, driven by efficiency gains. With efficient electrification, the study projects cumulative load growth of 24–52% by 2050 (see Figure ES-2, which summarizes this and other results). The 52% load increase projected in the ***Transformation*** scenario implies a 1.2% annual growth rate. While some of this load growth will be customer-supplied, utilities in most cases will supply capacity to ensure reliability. By comparison, annual load growth from 1990–2000 was 2.7%, dropping to 0.82%, on average from 2000–2010. For electric companies, such slow but steady growth can moderate potential rate impacts of investments for environmental compliance or grid modernization. Moreover, if guided, new flexible loads can improve grid efficiency and performance.

In all four scenarios, growth is led by the transportation sector, starting from minimal electric use today. Electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) quickly become cost-effective alternatives to conventional vehicles for most drivers. Heat pumps for space and water heating, along with electric technologies in industry and heavy transportation, are increasingly adopted in favorable markets, at rates constrained by stock turnover. The analysis suggests that the economic potential for electrification is compelling in many applications, yet realizing this potential requires removing policy and regulatory barriers that impact choice or limit supporting infrastructure. For customers, other barriers include a lack of innovative financing or risk aversion stemming from insufficient information on electrification technologies' value and benefits.

- *Final energy consumption decreases*

The modern era has been driven by significant growth in *final energy*—a measure of energy consumed across all fuel types at the end use. Most analyses suggest continued growth for decades to come.[4] In contrast, all four USNEA scenarios project falling final energy consumption. Continued growth in economic activity and energy services across all sectors of the economy is offset by efficiency improvements across the energy system, led by advances in individual end uses, such as lighting, variable speed motors, and more efficient internal combustion engine vehicles, as well as a shift from non-electric to more efficient electric technologies.[5] For the ***Reference*** scenario, the analysis projects a reduction in economy-wide final energy consumption of 22% by 2050, while electricity use grows by 32%. Final energy consumption declines further, and electricity use grows more in the ***Progressive*** and ***Transformation*** scenarios. This fundamental change in the composition of the energy system, which occurs in the ***Reference*** scenario and even in the ***Conservative*** scenario, illustrates the importance of establishing policies and regulations that adopt an economy-wide perspective of energy efficiency.

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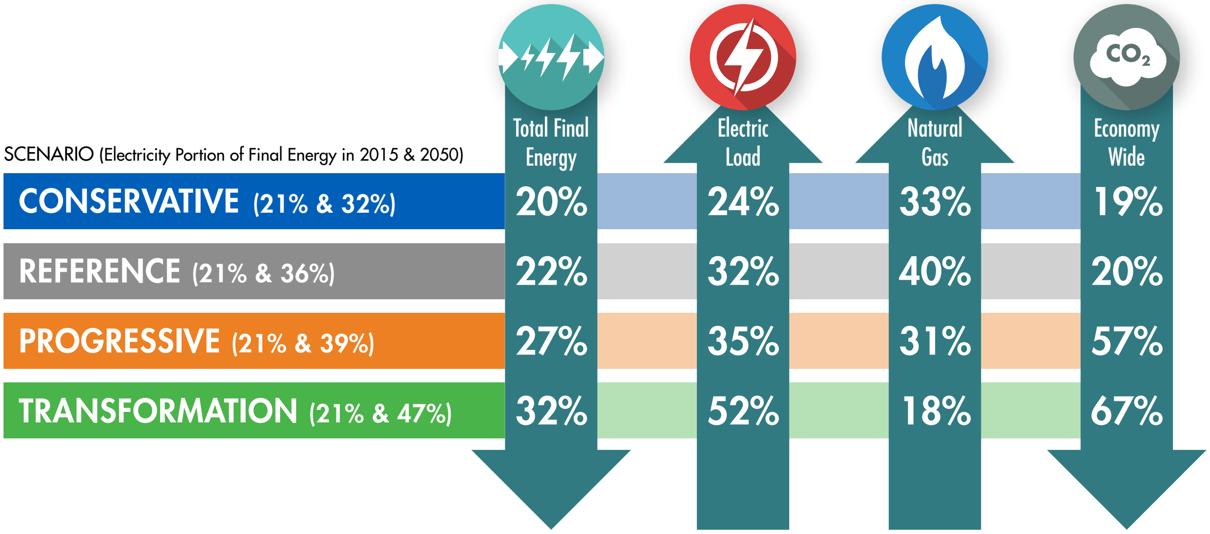
[4] For example, the Energy Information Administration's Annual Energy Outlook 2018 projects slow final energy growth for the United States across a wide range of future scenarios.

[5] Energy efficiency assumptions are informed by years of extensive laboratory testing and field demonstration projects, combined with observations of advances being driven by customer technologies–see for example, *The Third Wave of Energy Efficiency*, www.epri.com/#/pages/product/3002009354/.



SCENARIO (Electricity Portion of Final Energy in 2015 & 2050)	Total Final Energy	Electric Load	Natural Gas	Economy Wide
CONSERVATIVE (21% & 32%)	20%	24%	33%	19%
REFERENCE (21% & 36%)	22%	32%	40%	20%
PROGRESSIVE (21% & 39%)	27%	35%	31%	57%
TRANSFORMATION (21% & 47%)	32%	52%	18%	67%

Figure ES-2. High-level Overview of Modeling Results

- *Natural gas use increases*

With respect to natural gas in the United States, perceptions of a limited or dwindling resource a decade ago have been replaced with expectations that it will provide a low-cost, abundant fuel for the long term. Its importance to the electric sector has grown since the late 1980s and recently surpassed coal as the most-used fuel for power generation. Natural gas use continues to grow in all four EPRI scenarios based on its operational flexibility and an assumed ongoing cost around $4/MMBtu. The continued transition to gas creates both economic and environmental benefits (e.g., lower emissions than petroleum, which it often replaces in industry, and lower emissions than coal when used for electric generation). Direct natural gas use in industry and to fuel electric generation grows, while natural gas use in building heat remains relatively flat over time. Electric heat pumps with natural gas backup become attractive technologies in colder regions, utilizing the best features of both with dual-fuel capability potentially providing additional reliability.

In the *Transformation* case (which assumes a significant and growing carbon price), carbon capture and sequestration technology (CCS) enables natural gas to increase its share of electric generation, outweighing declines in the direct end-use of natural gas. In sensitivity analyses that assume that natural gas prices rise gradually to about $6/MMBtu by 2050, natural gas use still increases in all four scenarios despite the price rise.

As the electric sector's reliance on natural gas grows, it becomes increasingly important to incorporate natural gas supply modeling in reliability assessments. Recent disruptions in natural gas supply[6] highlight the importance of considering broader gas supply uncertainty in planning.

Another area in which natural gas may compete and that was not modeled in detail, is for combined heat and power. Electric grid modernization is key to unleashing the potential grid benefits of these technologies.

- *Low-carbon electric generation expands*

The carbon intensity of electric generation has fallen in recent years due to lower natural gas prices and increased penetration of solar photovoltaic (utility scale and distributed) and wind generation. Renewable energy continues to grow across all scenarios, driven by cost declines and state-level policies. In the carbon price scenarios, the share of wind and solar increases more rapidly as part of a diversified portfolio of low-carbon energy sources. Due to the declining marginal value of intermittent renewable energy, its economic penetration is ultimately limited, with nuclear and natural gas with CCS balancing the mix and providing firm capacity. The assumption that natural gas prices remain below $4/MMBtu across the scenarios

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[6] For example, a 2015–2016 Aliso Canyon natural gas storage leak in southern California led to the ongoing closure of the nation's fourth largest natural gas storage facility and the need for electric companies and state regulators to take extraordinary and costly measures to maintain electric system reliability in the Los Angeles basin. Extreme weather can also create disruptions. For example, extreme cold weather created significant challenges to regional energy systems in January 2014 due to the breakup of the Arctic polar vortex.

implies a greater role for natural gas with CCS in the carbon price scenarios, although the large-scale availability of this technology remains uncertain. In sensitivity analyses in which natural gas prices are assumed to rise gradually over 35 years to $6/MMBtu, wind, solar, and nuclear all have increased generation shares.[7]

As solar and wind generation capacity increases, the power system must operate more flexibly to accommodate their variable output. Although not explicitly modeled in this study, the addition of flexible loads through efficient electrification could emerge as a central strategy to efficient renewable generation integration.

- *Emissions decrease*

  In nearly every cost-effective application, electrification also lowers system-wide carbon emissions. Even absent a carbon policy, projected CO_2 emissions fall 20% by 2050 in the ***Reference*** scenario, driven by efficiency gains and efficient electrification. Although not modeled in this analysis, other EPRI research suggests that electrification can improve local or regional air quality by reducing emissions of criteria pollutants. Policies that provide an active signal to cut emissions (the ***Progressive*** and ***Transformation*** scenarios) lead to even greater environmental improvements—notably through a more rapid shift to electricity. For the ***Transformation*** scenario, electricity's projected share of U.S. final energy reaches nearly 50% by 2050, with emissions falling to nearly 70% below 2015 levels.

- *Pressures increase to modernize grid infrastructure, operations, and planning*

  As the end-use mix includes more vehicle charging and heating applications, seasonal low temperatures will drive heating demand, while reducing the efficiency of electric vehicles—resulting in a shift in overall loads to the winter months. While electricity demand in most U.S. regions peaks during the summer, peak loads could shift to winter by 2050 across the USNEA scenarios, assuming no efforts to actively manage loads. At the same time, these new electric loads provide significant opportunities for more flexible and responsive demand response, as well as storage. Realizing such benefits is contingent on investment in a flexible, resilient, and integrated grid[8] and clear electricity market signals. Such demand-side changes coupled with more diverse, dynamic electric supply, create an array of challenges and opportunities for system planners and operators.[9]

- *Technology innovation lowers costs and creates opportunities.*

  Realizing electrification's benefits depends on continued innovation in electric technologies to reduce costs and improve performance. The value is significant in all scenarios, but is greatest in the ***Transformation*** scenario, in which policy establishes a high value on lower emissions. Yet, economics alone and broader customer awareness will not be sufficient to realize the full potential for society. Industry stakeholders will need to build upon lessons learned from past successes, such as utility-administered energy efficiency programs to advance electrification technologies. In addition, effective rate designs coupled with policy and regulatory frameworks can be structured to support investment in electrification end-use technologies and enabling infrastructure, including a more resilient, integrated electric grid.

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[7] Given this study's focus on energy demand, only a few scenarios were examined for exploring generation. Key factors other than the price of natural gas, the value of carbon, and the availability of CCS that affect the technology mix include: renewable mandates, cost declines and technology change over time, relative costs of capital, the evolution of electricity markets (which affect both the total capacity of renewables and the relative economics of central versus distributed PV), the cost and availability of transmission, the cost and duration of storage, environmental constraints other than CO_2, the impact of renewable variability on the cost of the rest of the system, and flexible load. EPRI research has explored these factors in many other studies. Recent examples include a 2017 model comparison paper from NREL, EPRI, EIA, EPA and DOE, *Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective*, www.nrel.gov/docs/fy18osti/70528.pdf; and an article by John Bistline, "Economic and Technical Challenges of Flexible Operations under Large-Scale Variable Renewable Deployment" in *Energy Economics*, Vol. 64, May 2017.

[8] *The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources.* www.epri.com/#/pages/product/000000003002002733/.

[9] *Developing a Framework for Integrated Energy Network Planning (IEN-P): Ten Key Challenges for Future Electric System Resource Planning*, EPRI 3002010821 (forthcoming 2018).

ACTIONS TO REALIZE THE FULL BENEFITS OF EFFICIENT ELECTRIFICATION

The U.S. National Electrification Assessment brings into focus the potential for efficient electrification to transform the energy system. Yet it points to many actions that appear necessary to realize the full benefits. All require research, development, and demonstration to develop and test technologies, and to inform policy, regulation, and market choices—examining how alternatives may affect the grid and the energy system.

- *Accelerate technology research, development, and demonstration*
  - » **Cleaner electricity production.** Cleaner, more efficient power generation is essential to realize the full environmental benefits of efficient electrification. Electric generation has reduced its environmental footprint significantly over the past decade. Future gains depend on continued improvement of renewable energy, natural gas, coal, and nuclear technologies; increased flexibility in dispatch and improvements in storage; expansion of biofuels; and development and demonstration of CCS.
  - » **Grid modernization.** Grid investment must enable the dynamic matching of variable generation with demand, while supporting new models for customer choice and control. Investments are needed also to maintain reliability and enhance resiliency. Grid capacity planning and operation will need to address the integration of electric transportation networks with the grid through smart charging, fast charging, and storage utilization.
  - » **Continued, rapid advances in electric end uses.** Falling battery costs, digitalization, advances in materials, and increasing production scale can improve the efficiency and performance of a range of electric technologies, from automobiles to industrial equipment. Transformative shifts on the horizon include mobility-as-service models and autonomous vehicles, indoor agriculture, additive manufacturing, and electro-synthesis of chemicals.
- *Develop new analytical tools*
  - » **More in-depth studies of opportunities and challenges of efficient electrification.** The USNEA provides a starting point for considering and examining efficient electrification, offering insights and a framework for additional analyses. For the United States and other countries, detailed regional studies are needed for a realistic understanding of the costs, the benefits, and the barriers that will drive customer choices in varied circumstances.
  - » **New cost-benefit frameworks for assessing individual electrification projects.** New methods for comparing options for providing energy services are essential to support informed regulation and to implement programs that address barriers to customer adoption of technologies. Improved understanding of diverse customers' perspectives is essential in building more useful models.
- *Expand focus on reliability and resiliency*
  - » **New metrics for reliability.** As the electric system increases its reliance on variable renewables and just-in-time delivery of natural gas, it is important to re-examine concepts of reliability that historically focused solely on the electric system and on framing resource adequacy, primarily annual peak demand. Looking ahead, system reliability may be framed in multiple hours by comprehensively considering system flexibility, natural gas delivery risk, and other factors.
  - » **Greater focus on electric system resiliency.** The scenarios depict an expanding role for electricity in the energy system, which heightens requirements for resiliency with respect to both natural forces (e.g., extreme weather) and physical or cyber attacks. As electric systems "go digital" from generation through billions of connected devices, the points of entry for attack increase exponentially. That same digital capability can be harnessed to locate, isolate, and recover from both natural disruptions and attacks.

- *Inform policy, regulatory, and electricity market designs*
  - **Coordinated, economy-wide policies.** The dramatic sectoral shifts projected in all four scenarios underscore the value of taking a broad view of energy policy, rather than addressing issues piecemeal. Uncoordinated approaches for electricity, transportation, and industry or across energy sources create unnecessary costs. Broadly considered policies may enable more effective, less disruptive shifts, with respect both to the energy sector and society. For example, for environmental policy, this assessment's modeling assumes a consistent carbon signal applied to all sectors of the economy. Yet today no country takes this approach, choosing various policy approaches for different sectors. Policies focused on one sector can limit the interactions among multiple sectors to achieve broader goals. For example, efficient electrification could reduce economy-wide emissions even while leading to a relatively small increase in electric sector emissions.
  - **Updating energy efficiency codes.** A review of energy efficiency measurement and cost tests (e.g., for appliances, heating, and transportation) is needed to remove fuel bias and to frame regulations that enable efficient electrification and encourage traditional energy efficiency.
  - **Facilitating market transformation.** Targeted programs—similar to efforts with energy efficiency—may be needed to address barriers to efficient electrification, where it makes sense economically and among public priorities.
  - **Electricity market designs to send consistent signals to both supply- and demand-side.** With new electric supply and demand technologies projected to emerge, it becomes increasingly important to value energy, capacity, flexibility, locational value, storage, and other attributes. EPRI's research on advanced energy communities with zero net energy and all-electric residences clearly shows the need for valuing both energy and grid connectivity.[10]

CONCLUSION AND NEXT STEPS

EPRI's U.S. National Electrification Assessment brings into focus the potential for efficient electrification to create value for customers and society, looking across energy end-use sectors. Its analyses point to actions needed to define benefits more precisely and to establish an effective transition. EPRI is moving forward on many fronts, with near-term actions that include:

- Detailed, state-level assessments to examine the costs, benefits, drivers, barriers, and challenges to efficient electrification, integrating local knowledge and circumstances. EPRI is pursuing similar collaborations internationally. These studies will examine a broader array of drivers for investment and transformation of energy systems, including local air quality.
- A benefit-cost framework in 2018 for assessing individual efficient electrification projects to support investment and inform regulatory decision-making.
- Establishing electric technology centers of excellence at universities and other institutions to create, demonstrate, and field test a range of emerging electric technologies.
- Expanded research in resiliency and cyber security to address emerging challenges for the electric sector and for society as it continues to electrify.
- Facilitating awareness among all industry stakeholders and customers through active outreach. Initiate an annual international conference for diverse groups that will drive the electric future—generators small and large, grid operators, end-use vendors, universities, research labs, regulators, policymakers, city governments, businesses, smart communities, and individual customers—to consider, pursue, and realize the benefits of efficient electrification.

In addition, many of EPRI's ongoing research programs address efficient electrification as their primary scope or as part of a broader or supporting scope of work. Chapter 6 provides information on these programs, or they can be found online at www.epri.com/#/portfolio/en/2018/home.

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[10] See, for example, *Grid Integration of Zero Net Energy Communities*. https://www.epri.com/#/pages/product/3002009242/.

1. INTRODUCTION

BACKGROUND

Based upon a multi-year, collaborative effort to examine the forces that are changing the world's energy systems, the Electric Power Research Institute (EPRI) introduced in 2017 its concept of an Integrated Energy Network. Its essential idea is that effective integration of energy supplier and user networks can and will lead to more reliable, flexible, and affordable energy services.

This paper examines a key theme of the Integrated Energy Network: the critical and growing role that electricity will play in the future energy system. Since its commercial beginnings in the late 19th century, electricity's role in the energy system has grown steadily, reaching 3% of final energy consumption in 1950 and approximately 21% today. This growth has been driven primarily by lighting, cooling, refrigeration, entertainment, and communications—meeting demands that electricity has dominated.

Electricity's importance is poised to continue to grow, making significant inroads in non-traditional uses such as transportation, expanding its role in space and water heating, and meeting a growing array of energy needs across the economy. For many uses, electricity may serve as a more efficient and economical alternative, with lower environmental impact, offering equal or better service. EPRI calls this "efficient electrification," and based upon extensive research, analysis, and discussion, considers this a central issue for the energy sector.

THE U.S. ENERGY SYSTEM TODAY AND OPPORTUNITIES FOR CHANGE

The U.S. economy relies on electricity, natural gas, petroleum products, coal, and various forms of bioenergy to provide energy services across the transportation, buildings, and industry sectors. Figure 1-1 illustrates U.S. final energy (energy consumed at end use) by application and fuel for 2015.

In 2015, non-electric energy supplied almost 80% of end-use energy consumption. Efficient electrification can, in theory, substitute for many of these uses, but substitution is most likely where viable electric technologies are available, economical, provide better service, and can meet other societal needs such as reducing air pollution, water use, and carbon emissions.

Over 40% of final energy in the United States is used for transportation, and nearly two-thirds of that (a quarter of U.S. total final energy) is consumed as liquid fuels for light-duty passenger vehicles, providing a large opportunity for efficient electrification for on- and off-road applications, large and small. Petroleum fuels almost all transportation services today, but attractive electric options are expanding, driven primarily by battery cost and performance improvements. Given rising demand for transportation, electric options provide a large opportunity for improved efficiency and lower emissions, while providing equal or better service.

Electricity's role in the energy system has grown steadily from 3% of energy consumption in 1950 to 21% today.

With increasingly attractive electric technologies, many consumers could choose electric alternatives in the future—if non-economic barriers can be overcome.

Electric technologies often provide an array of benefits—lower cost, fewer emissions, and less energy use while providing equal or better service.

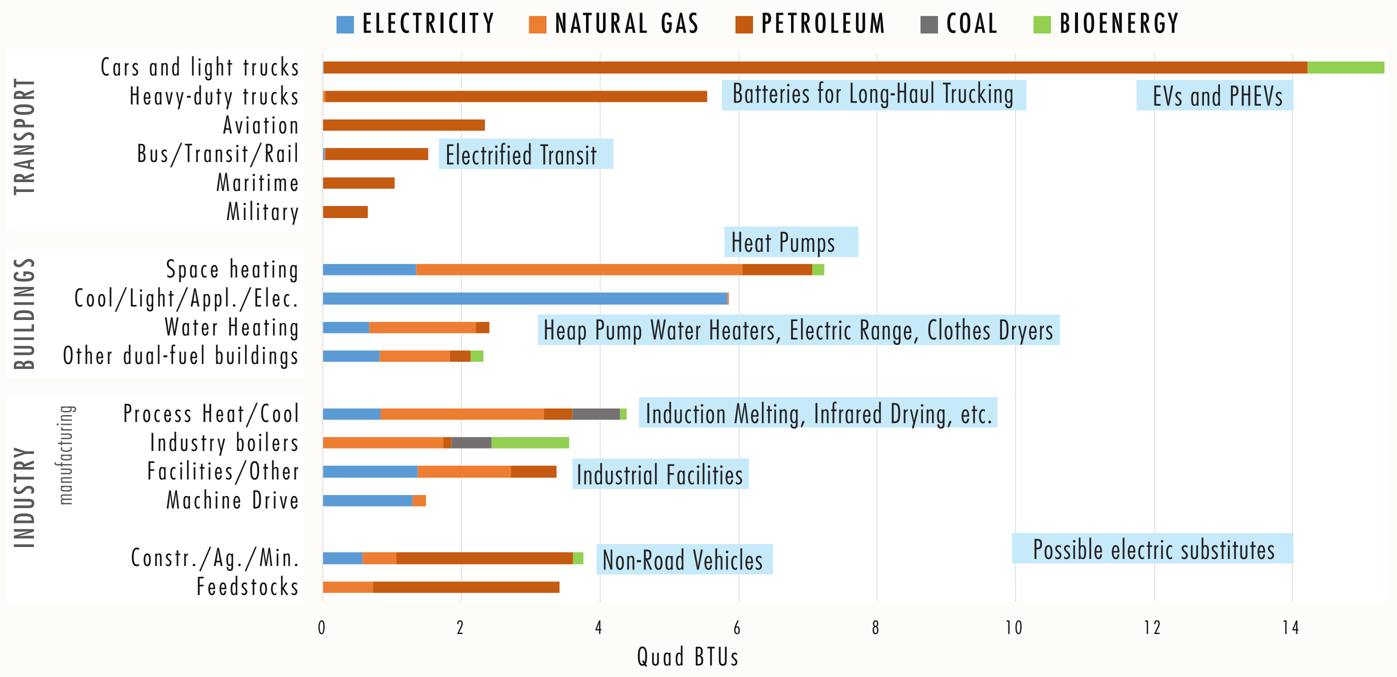

Figure 1-1. 2015 U.S. final energy by fuel and application. Possible electric substitutes in blue.

In buildings today, natural gas provides approximately two-thirds of space and water heating final energy, but significant opportunities are emerging for efficient electric technologies to replace less efficient electric resistance heating and to combine with or displace natural gas in some heating applications.

The industrial sector presents a range of specialized opportunities—such as process heat and cooling, facility operations, non-road vehicles, and machine drive—where electric technologies can reduce cost, increase productivity, and improve workplace health and safety. While these opportunities may be small individually, their aggregate impact can be substantial.

UNDERSTANDING EFFICIENT ELECTRIFICATION

Detailed case studies illustrate that efficient electrification can potentially provide a range of benefits to individual customers, society at large, and utilities. Figure 1-2 summarizes some of these benefits.

Some electric technologies can provide one or two of these benefits. Others can arguably provide almost all of them. For example, commercial truck stop electrification can provide lower cost, energy savings, lower emissions, productivity increases, and enhanced worker safety.

METRICS	BENEFIT		
	CUSTOMER	UTILITY	SOCIETY
ECONOMIC EFFICIENCY -it costs less	✓	✓	✓
ENERGY EFFICIENCY -uses fewer BTUs overall	✓	✓	✓
ENVIRONMENT -CO_2 savings -emission reductions, water savings	✓	✓	✓
GRID FLEXIBILITY	✓	✓	✓
ECONOMIC DEVELOPMENT -jobs creation and retention -development of community assets	✓	✓	✓
PRODUCTIVITY IMPROVEMENTS -plant output increase -reduction in energy intensity -improved product quality	✓		✓
WORKER SAFETY IMPROVEMENTS -reduced lost time and accidents	✓		✓

Figure 1-2. Efficient Electrification Potential Benefits. Metrics in blue are explicitly modeled in the USNEA. Other potential benefits have been explored in prior EPRI research or case studies.

The U.S. National Electrification Assessment (USNEA), which is the focus of Chapters 2, 3, and 4, explicitly considers economic efficiency, energy efficiency, and CO_2 emissions benefits. Other potential benefits have been documented in case studies and will be examined in more depth in a series of state-level assessments EPRI plans to conduct in 2018–2019.

Economic Efficiency, Energy Efficiency, and CO_2 Comparisons–A Systems Approach

In comparing fuels for providing energy services, energy use, emissions, and other factors, consideration must extend from fuel extraction through end-use service.

At the point of use, electricity often is more efficient and cleaner than non-electric alternatives. Consider these comparisons, on a Btu basis:

- For electric vehicles, pump-to-wheels fuel consumption is one-third to one-quarter that of an efficient internal combustion engine, with no emissions at point-of-use.
- For space heating, while 80–90% of the energy consumed by a natural gas furnace is delivered as useful heat, electric heat pumps can deliver the same service by consolidating and moving heat from air- or ground-source reservoirs, using one-third to half as much input energy, with no emissions at point of use.

However, end-use efficiency is not the whole story. Electricity must access fuel, be generated, transmitted, and distributed, creating losses and emissions that derive from the generation mix, which changes over hours, seasons, years, and decades and by location. Similarly, gasoline is produced in refineries and transported by truck to fueling stations, which entails losses and emissions.

Figures 1-3a and 1-3b provide diagrammatic examples of important factors in comparing energy use, emissions, and cost for transportation and for heat. For simplicity, these examples assume that all electricity is produced by a natural gas combined-cycle plant. In contrast, the modeling results described in Chapters 3 and 4 provide more sophisticated regional simulations of the electric system through 2050 as it develops and changes. In addition to various natural gas technologies, regional electric systems include renewable generation (hydroelectric, solar, wind, other), nuclear, and coal along with possible future deployment of emission control technologies such as carbon capture and sequestration. These generation choices affect energy efficiency, emissions, and cost.

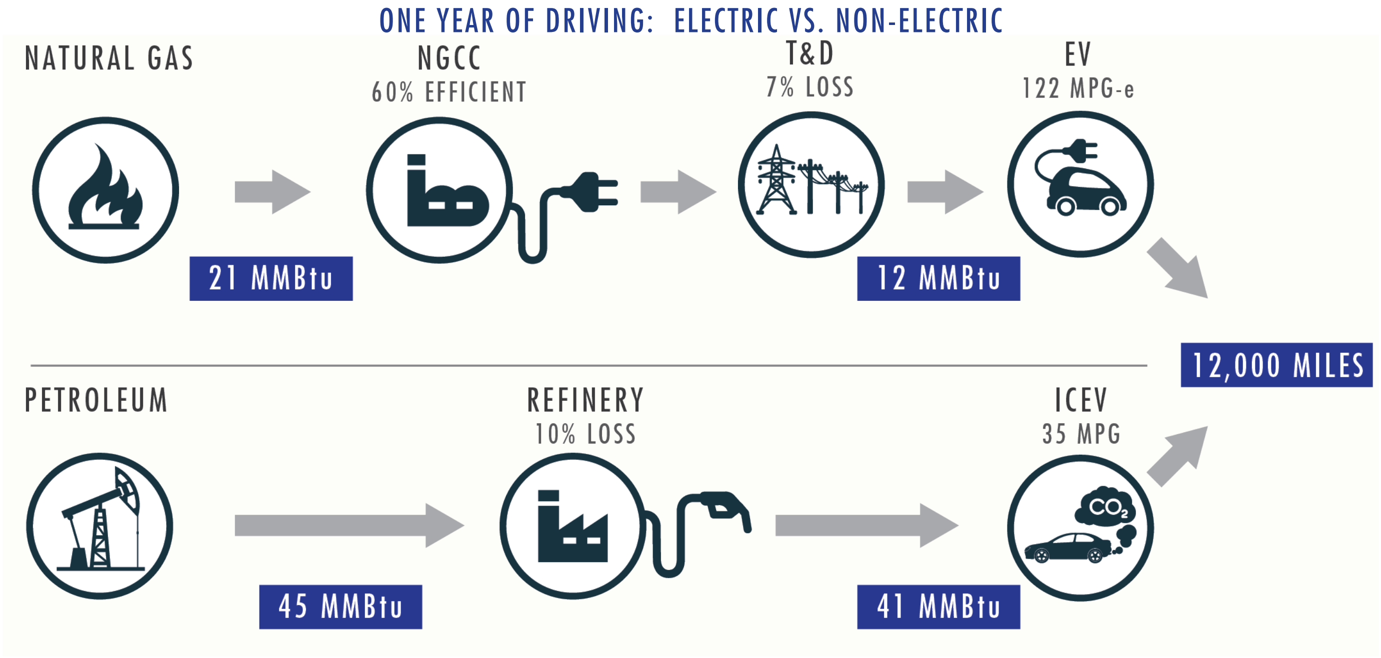

Figure 1-3a. Electricity versus gasoline for light-duty vehicles. *On average a U.S. vehicle is driven approximately 12,000 miles per year. The diagram illustrates a simple example comparing energy consumption between an ICEV and an EV assuming electricity is generated by a natural gas combined-cycle (NGCC) power plant. The ICEV uses 3.5 times more final energy than the EV, and when losses in transmission and conversion are considered, over twice as much primary energy. In this example, the ICEV emits about three times more* CO_2 *per mile than the EV. Non-electric fuel transportation losses are not shown but are generally small.*

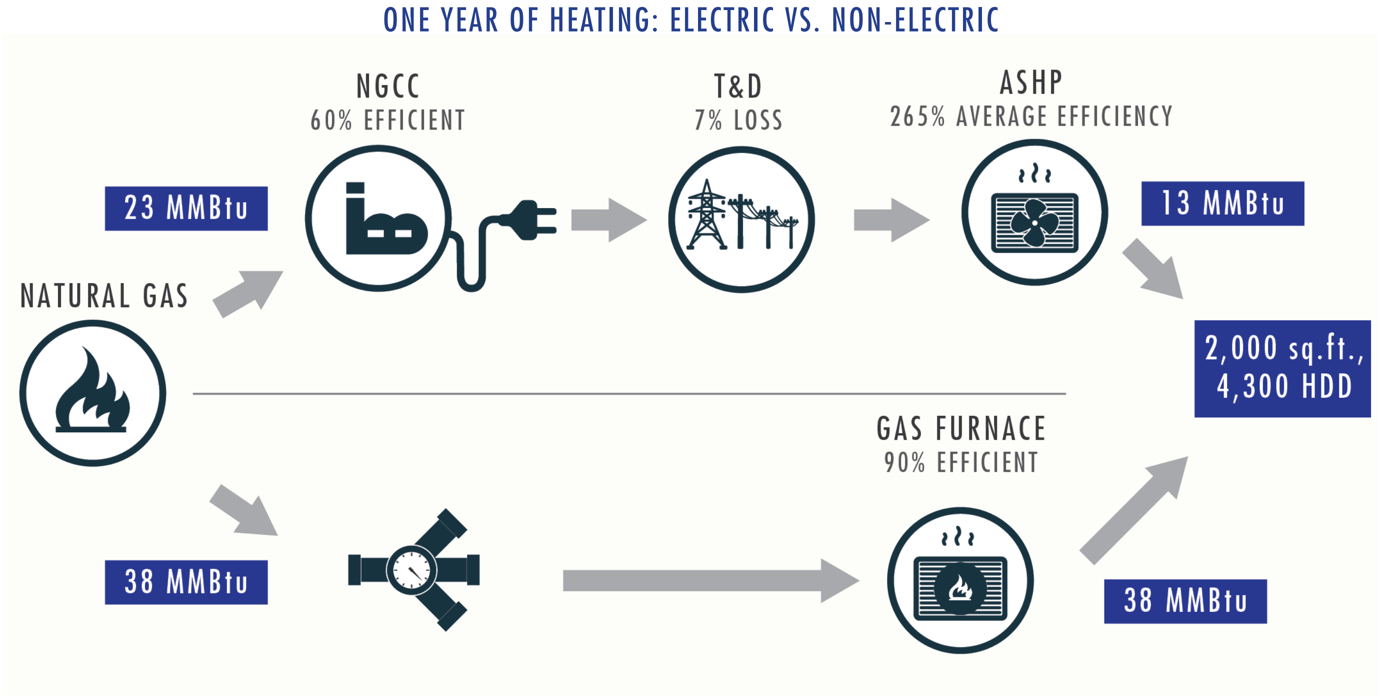

Figure 1-3b. Electric heat pump versus natural gas furnace. *Consider a 2,000 sq.ft. single-family home in Atlanta, GA, a location with around 4,300 heating-degree days (HDD) per year on average. The diagram illustrates a simple example comparing energy consumption between an air-source heat pump (ASHP) and a gas furnace assuming electricity is generated by a natural gas combined-cycle (NGCC) power plant. The gas furnace uses 3 times more final energy than the ASHP, which moves heat from outside into the house rather than creating heat through combustion. When losses in transmission and conversion are considered, the difference is reduced, with the furnace using roughly 1.6 times as much primary energy as the heat pump and therefore emitting 1.6 times more* CO_2.

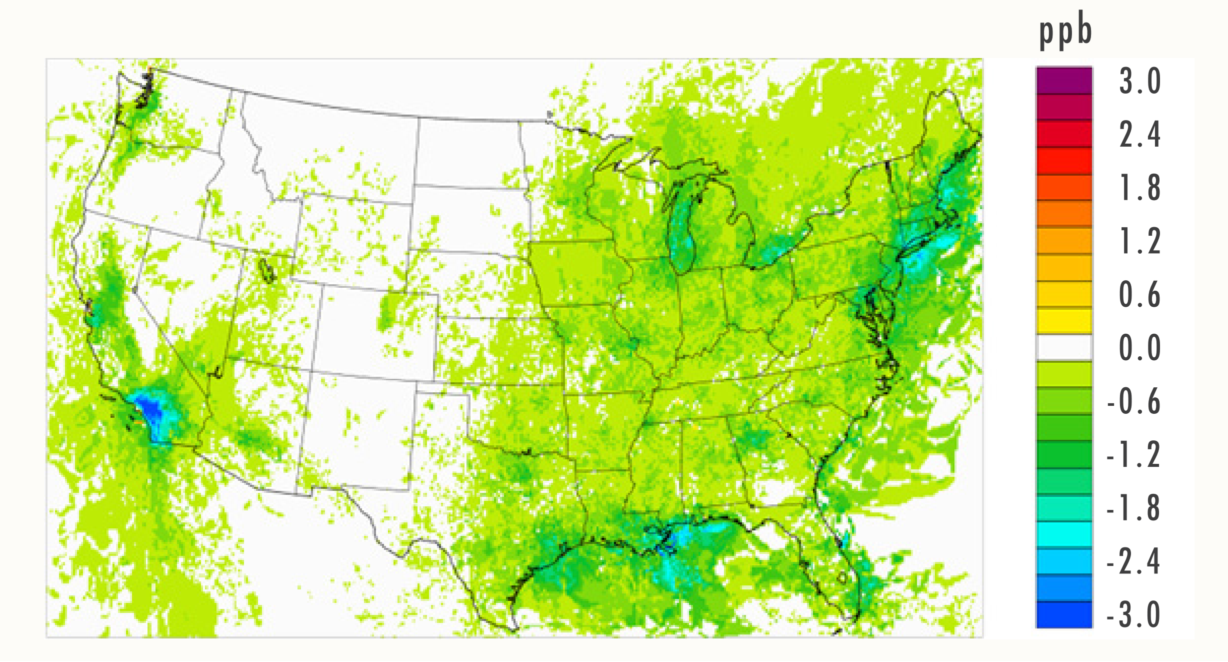

Figure 1-4. Reductions in ozone due to transportation electrification (results for 2030; based on fourth highest daily maximum eight-hour ozone concentration).

Air Emissions

For many end uses, air emissions are a key driver for electrification. Local air pollution has led major cities around the world to consider moves to electric public transportation and to limits on non-electric vehicles. Although air quality impacts are not explicitly modeled in the USNEA, EPRI has conducted past research to understand these potential benefits. Jointly with the Natural Resources Defense Council, EPRI concluded that "…widespread use of electric vehicles—including lawn and garden equipment and heavy industrial equipment such as forklifts—could radically improve air quality, particularly in densely populated urban areas…" (See Figure 1-4).[11] In recent years, substantial attention has been directed to electrification in the context of cutting global CO_2 emissions. But findings that electrification can lower local and regional pollutants underscore how both policymakers and consumers can look to electrification to address an array of natural resource impacts. This points to electrification's potential usefulness in diverse strategies to make energy services cleaner and to reduce or mitigate many different environmental impacts.

Water Use

Water conservation is a key focus for certain industries and regions. With growing concerns regarding water availability and scarcity, the potential to reduce water use is important in assessing electric technologies' costs and benefits. As with energy efficiency and emissions, a system perspective is important in comparing alternatives because water use for extracting fuels and producing electricity can vary widely across regions.

A first screen is to identify technologies that are more water-efficient at the end use. An EPRI Quick Insight Brief, *Water Saving Opportunities with Electric Technologies,*[12] provides highlights from studies that examined end-use water use, describing several electric technologies in residential, commercial, industrial, and agricultural applications that can save water:

- **Heat Recovery Chillers for Commercial and Industrial Applications.** Heat recovery chillers provide heating and cooling in large commercial and industrial facilities. Capturing and utilizing heat, which otherwise would have been rejected through a cooling tower, results in significant water savings by eliminating water losses in the cooling tower.

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[11] An overview of the study is provided at www.epri.com/#/pages/product/000000003002006880/). The report that describes the air quality results in detail is: *Environmental Assessment of a Full Electric Transportation Portfolio, Volume 3: Air Quality Impacts*. EPRI report 3002006880.

[12] Reference … https://www.epri.com/#/pages/product/3002011028/

- **Residential Air Source Heat Pumps for Space Conditioning.** When replacing evaporative (swamp) coolers in homes, air source heat pumps can yield significant water savings. While less than 1% of homes in the United States have evaporative coolers, they are prevalent in arid areas where water scarcity can be an issue (e.g., more than 40% of homes in Nevada with central space conditioning).
- **Indoor Agriculture.** Indoor agriculture provides an artificial all-day, all-season agricultural growing environment. Water recirculation in these facilities has been estimated to reduce water use by 90% or more in recent applications. The overall scope of these savings could be regionally important if the market for these facilities continues to expand.
- **Infrared Drying and Infrared Peeling of Tomatoes.** Infrared technologies, which use no water directly, could replace steam or caustic chemical processes currently used to dry materials and to perform processes such as peeling tomatoes, with potential water savings and other environmental benefits.
- **Heat Trace in Residential Application.** A resistive cable can keep water in pipes warm, reducing water wasted as customers wait for hot water to reach their sink, bathtub, or shower.

Grid Flexibility

Automobiles, heavy transport, heat pumps, heat pump water heaters, and many other efficient electrification technologies can potentially increase grid flexibility—an attribute which becomes more valuable as solar and wind contribute a greater fraction of generation. For transportation, systems that influence the time and speed of vehicle charging can have both local and overall grid benefits, with even greater impact if the future grid can effectively utilize vehicle batteries as storage. Car charging flexibility could shift daily load shapes in the near-term and perhaps shift loads from day-to-day as car ranges increase. Heating end uses also have flexibility because of the inertia of insulated hot water tanks and buildings. End-use systems can be controlled to meet grid needs with indiscernible impacts on comfort. Key challenges to achieving this flexibility are to develop the hybrid control systems (integrating supply and demand resources) and understanding customers' decision making so that attractive and effective programs can be developed.

Economic Development

While there is extensive literature on electrification and broad-scale economic development, there has been little attention focused on the economic development impacts of efficient electrification. One possible benefit is regional. For example, emission-free end use of energy, which electricity provides, allows economic development to occur in areas where other energy use might be limited due to air quality or safety concerns. And new concepts that are enabled by electricity, such as indoor agriculture, could flourish in urban settings where traditional agriculture is impossible.

In the longer term, efficient electrification is a key enabler for continued broad-scale economic development while society aims to achieve other goals, such as carbon emission reductions. Without electric technologies, such goals may not be economically or politically feasible.

Productivity

In commercial and industrial applications, productivity is a key factor in evaluating alternative technologies. An EPRI Quick Insight Brief, *Productivity Improvements and Benefits of Efficient Electrification,*[13] provides examples of the types of gains that can be realized. A few of the examples from that brief are mentioned below:

- **Electric Forklifts.** Material handling vehicles are used in diverse industries to transfer cargo, stock, and pallets. Forklifts (also known as lift trucks or fork trucks) are one of the most widely used material-handling vehicles. Technology improvements have led to widespread adoption of electric forklifts, even for demanding multi-shift operations, capturing almost two-thirds of the U.S. market and 70% of the European market. Productivity gains derive primarily from reduced downtime for maintenance and fueling (batteries operate for two shifts and recharge when the plant is closed).

- **Commercial Truck Stop Electrification.** For every 14 hours of driving, the U.S. Department of Transportation requires long-haul truck drivers to rest for 10 hours. Often drivers rest in truck cabs, idling the truck's engine to heat or cool the cab or power appliances such as a television, microwave, or refrigerator. Plugging in trucks instead of idling engines reduces fuel use and maintenance costs 40–70%, reduces local emissions and noise, and provides drivers a quiet, vibration-free rest stop. Because the truck is not idling extensively, engine life increases due to reduced wear and tear of engine parts. Engine maintenance intervals can be longer, improving productivity and reducing downtime. Compared with heavy duty trucks idling an average of six hours per day, the savings can be substantial.

- **Electric Induction Cooking Ranges and Electric Fryers.** Electric induction cooking ranges heat quickly, offer precise temperature control, and eliminate the open flame, which can improve safety. Food can be cooked faster, improving commercial kitchens' productivity. Electric fryers operate at lower temperatures, which saves energy, reduces oil breakdown, and uses less oil. Electric fryers heat and reheat faster than gas units, which is an important factor in the fast food industry.

- **Ultraviolet (UV) Curable Coatings.** UV coatings cure in seconds, rather than the minutes or hours required with thermal processes, enabling faster line production. UV curing enables faster startups and shutdowns, with lower energy consumption. "Standby" energy use can be reduced because UV lamps turn on and off almost instantly, with minimal energy or time lost, relative to the waiting required for ovens to heat prior to starting or resuming production.

Worker Safety

Electric technologies in commercial and industrial facilities can reduce exposure to chemicals and emissions, ambient noise, and hazardous environments as associated with open flame and high temperature. An EPRI Quick Insight Brief, *Potential Health and Safety Benefits of Efficient Electrification,*[14] provides several examples:

- **Electric Forklifts.** Replacing gasoline- or diesel-fueled forklifts with electric forklifts reduces health effects related to on-site emissions such as carbon monoxide (CO) and excessive noise from internal combustion engines.

- **Airport Ground Support and Gate Electrification.** Electric ground support equipment (e.g., baggage tractors, push back tractors, and belt loaders) reduce on-site emissions of carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter and reduce the threat to hearing from excessive noise. Grid-connected gate electrification can eliminate the emissions and noise associated with idling aircraft.

- **Commercial Truck Stop Electrification.** Electric truck refrigeration units and truck stop electrification reduce diesel idling at rest stops, resulting in better health conditions for drivers and overall reductions in on-site emissions and criteria pollutants. A 1996 study states that truck stop electrification has the potential to reduce volatile organic compounds, nitrogen oxides, carbon dioxide (CO_2), and CO by 99%, 98%, 68%, and 98%, respectively.

- **Other electric technologies for which case studies suggest improved worker health and safety include:**
    - Commercial Electric Fryers and Griddles

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[13] Reference … https://www.epri.com/#/pages/product/3002011765/

[14] Reference … https://www.epri.com/#/pages/product/3002011450/

  - Ultraviolet (UV) and Ozone Water Treatment
  - Induction Melting
  - Electric Ladle Preheating
  - Metal Fabrication

Why Efficient Electrification Now?

Electric vehicles were sold commercially in the late 19th century, heat pumps were first built in the 1850s, and various electric technologies have served niche applications for decades. The growing interest in these technologies today is driven by several factors:

- **Lower cost and better performing electric technologies.** Plug-in vehicles are increasingly viable for many as costs drop and batteries improve. Digitalization has led to substantial improvements in both mobile and stationary technologies, such as heat pumps.
- **Cleaner electricity.** Environmental control technologies have reduced fossil-fueled power plant criteria air emissions by more than 80% over the past two decades. Natural gas-fired generation's growth, coupled with that of renewable energy and continued nuclear generation, have reduced electricity sector CO_2 emissions 18% since 2005, and further emission reductions are likely given the low cost of natural gas, the declining cost of renewables, and state/local policies.
- **Social consensus for a cleaner environment.** Local and regional air quality today, reduced risk of climate effects in the future, and stewardship of water resources provide additional impetus to efficient electrification.

Why is it useful at this time to consider more focus, initiative, and momentum for electrification?

It takes decades to make large shifts in energy-using equipment. Consumers replace their water heater every 10–15 years, their space heating every 20 years or so, and their car about every 7 years. Often, replacement is necessitated by old equipment failing, prompting the owner to replace the equipment urgently and defaulting to the incumbent technology. It can require effort to consider alternatives and to provide customers with an understanding of the immediate value of a new technology and its increasing benefits over time. For example, as the power system becomes cleaner, electric technologies bought today for end use can be expected to have less environmental impact each year they are operated.

Emerging electric technologies create new opportunities for cleaner, better energy service.

The energy system is changing rapidly. With long lead times for installing energy-using equipment, a forward-looking perspective is valuable.

Many analysts, companies, governments, environmental groups, and citizens are talking about electrification.

The U.S. National Electrification Assessment provides a transparent modeling platform to support discussion, focus research, and inform policy/regulation.

The U.S. National Electrification Assessment in Context

The USNEA is among many analytical efforts globally that are considering electrification. Most of these studies target environmental improvement and specifically, reducing CO_2 emissions. Based upon hundreds of published scenarios produced by dozens of models around the world,[15] the United Nations Intergovernmental Panel on Climate Change (IPCC) indicated that decarbonizing electricity coupled with accelerated electrification is a "key component" for cost-effective, deep cuts in global emissions. The European Commission's detailed examination of climate policy for Europe, *Energy Roadmap 2050*, projects a near doubling of electricity's share of "final energy"[16] from 20% today to 36–39% in 2050.[17] National studies—particularly in Europe—have examined in depth the economics, technologies, and structural challenges associated with electrification, combined with extensive renewable deployment and electricity-to-gas and other pathways.[18] Edmonds, et al., in one of the few papers to examine electrification in detail globally and regionally, concluded the tighter the carbon constraint, the greater the role of electricity—even using conservative assumptions regarding improvements in power generation technology.[19] EPRI research consistently supports this conclusion.[20] There are many ways to cut emissions, but these studies from across the globe underscore that, both for specific and broad application, electrification is crucial to making emission controls cost-effective and affordable.

In the United States, recent analytical studies by government, private firms, and environmental organizations have added insights. As part of a larger electrification study, the U.S. Department of Energy recently released an assessment of the cost and performance of electric end-use technologies.[21] Brattle explored the potential load and electric system impacts of a shift to electric transportation and heating.[22] The Northeastern Energy Efficiency Partnership examined state-level electrification potential in the northeast United States.[23] The Regulatory Assistance Project (RAP) is identifying regulatory barriers impeding electrification.[24] The Natural Resources Defense Council (NRDC) and EPRI published

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15. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

16. Electricity's share of final energy is one metric used to provide an aggregate, quantitative measure of electricity's role in the energy system. Electricity's role has grown over the last century largely driven by increased use of electricity-dominated end-uses (e.g., lighting, air conditioning, home appliances, communication, entertainment). Electrification—defined here as switching from fossil fuel end uses to electric ones driven by technology advances or efficiency/environmental goals—appears poised to accelerate this growth.

17. European Commission: *Energy Roadmap 2050,* European Commission, 2011.

18. For example, see *National Grid's Future Energy Scenarios* at http://fes.nationalgrid.com/fes-document/.

19. Edmonds J. A., T. Wilson, M. A. Wise, and J. P. Weyant (2006). Electrification of the Economy and CO_2 Emissions Mitigation. *Environmental Economics and Policy Studies 7*, 175-203.

20. Rose S., R. Richels, G. Blanford, and T. Rutherford (2016). "The Paris Agreement and Next Steps in Limiting Global Warming."

21. The National Renewable Energy Lab is leading a multi-year Electrification Futures Study. The first in a series of reports was released in late 2017, Jadun, Paige, Colin McMillan, Daniel Steinberg, Matteo Muratori, Laura Vimmerstedt, and Trieu Mai. 2017. *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-70485. https://www.nrel.gov/docs/fy18osti/70485.pdf.

22. The Brattle Group's 2017 white paper, *Electrification: Emerging Opportunities for Utility Growth* (http://files.brattle.com/files/7376_electrification_whitepaper_final_single_pages.pdf), made calculations based on EIA Annual Energy Outlook scenarios to estimate load growth and CO_2 reductions that could result from significant electrification of transport and heating. Brattle released a briefing paper in 2018, *New Sources of Utility Growth: Electrification Opportunities and Challenges* (http://files.brattle.com/files/13526_new_sources_of_utility_growth_electrification_opportunities_and_challenges.pdf) that provides a fresh perspective on this study.

23. The Northeastern Energy Efficiency Partnership completed a study in mid-2017 that assesses the opportunity, costs, and benefits of adopting "strategic electrification" as a key strategy for decarbonization in New York and New England, *Northeastern Regional Assessment of Strategic Electrification*. July 2017. http://www.synapse-energy.com/sites/default/files/Strategic-Electrification-Regional-Assessment-17-018.pdf.

24. The Regulatory Assistance Project has co-authored papers and published blogs on the promise of "beneficial electrification" and the need to update regulation and efficiency metrics to fully enable electrification e.g., ("Environmentally Beneficial Electrification: The Dawn of 'Emissions Efficiency," *The Energy Journal*. Vol. 29, Issue 6, July 2016).

reports examining air and greenhouse gas benefits of electric transportation.[25] Electric companies such as Edison International are outlining opportunities, potential paths, and impediments to electrification.[26]

With the U.S. National Electrification Analysis, EPRI offers leading-edge modeling to understand key drivers, potential barriers, and the possible pace of electrification from many distinct viewpoints: customers, power transmission and generation, equipment providers, and the ultimate impact on environment and the economy. The EPRI modeling differs from other studies in many respects by including detailed representation of customers' economic trade-offs, full integration of electric demand and supply choices, and an outlook on the rate of technological change, particularly for energy efficiency. This assessment's view is informed by EPRI's years of extensive laboratory testing and field demonstration projects.

This national assessment will be followed by more detailed state-level and international studies examining opportunities and regional realities of efficient electrification.

Organization of the Report

Following this chapter:

- Chapter 2 introduces the modeling approach, describes its scenarios, and highlights key assumptions.
- Chapter 3 provides key sectoral modeling insights for transportation, buildings, and industry.
- Chapter 4 elaborates on the seven key, economy-wide insights highlighted in the Executive Summary.
- Chapter 5 discusses four key actions to realize the promise of efficient electrification.
- Chapter 6 presents EPRI's next steps, highlighting programmatic research and an EPRI Board of Directors' initiative on Efficient Electrification.

US-REGEN model structure and assumptions are provided in a separate report, US-REGEN Model Documentation (https://www.epri.com/#/pages/product/3002010956/).

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25. The Natural Resources Defense Council (NRDC) has jointly authored several papers with EPRI that examine the greenhouse gas and air quality benefits from transport electrification, *Environmental Assessment of a Full Electric Transportation Portfolio* (EPRI Reports 3002006875, 3002006876, and 3002006880; 3002006881). NRDC has separately published policy documents aimed at spurring transport electrification.

26. Edison International released a white paper in November 2017 that provides their perspective on electrification's role in meeting California's goals, *The Clean Power and Electrification Pathway: Realizing California's Environmental Goals* (https://www.edison.com/content/dam/eix/documents/our-perspective/g17-pathway-to-2030-white-paper.pdf).

2. MODELING APPROACH, SCENARIOS, AND KEY ASSUMPTIONS

The National Electrification Assessment employs US-REGEN,[26] a multi-region, energy-economy model developed by EPRI. The assessment examines four core scenarios along with sensitivity analyses that vary a few key assumptions. The assessment requires many assumptions regarding technology cost and performance, fuel prices, economic growth, and the structure of the economy. This chapter introduces the US-REGEN model and summarizes the scenarios examined and some of the key assumptions.

US-REGEN Model

EPRI's US-REGEN model is used to project the evolution of the U.S. energy system. US-REGEN combines a state-of-the-art electric sector capacity planning and dispatch model with a newly developed and uniquely capable end-use model (Figure 2-1).

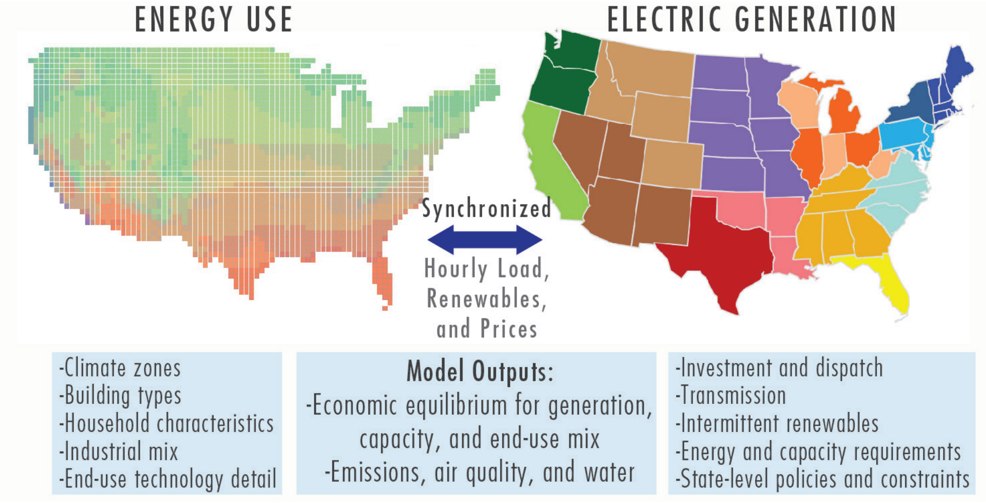

Figure 2-1. Overview of the US-REGEN model. The US-REGEN model comprises linked models of electricity supply and energy use. Analyses in this report use a 15-region version of the model. Analyses can alternatively be conducted at the state level. The detailed electric model was linked with a new energy use model, which simulates technology choices by customer segment for an array of energy services, with emphasis on those services for which fuel substitution is possible or likely. In the model, heating options were evaluated at a very granular level using climate zones depicted on the left map.

A new model of energy use coupled with a detailed model of the grid provides a fresh, integrated perspective on customer choice and system performance.

A low natural gas price path was used in all core scenarios, in part, to provide a more difficult economic hurdle for efficient electrification.

Electric vehicle purchase prices are assumed to be higher than ICEV prices through 2050.

However, lower fuel and maintenance costs mean total ownership costs of EVs are lower by 2025 for many who drive 12,000 miles a year or more and in later years for those who drive less.

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[27] US-REGEN is an integrated energy-economy model examining and connecting energy supply and demand over time to yield consistent projections that include changing system load shape and demand consistent with hourly electricity prices. Since its beginning in 2009 US-REGEN model development has been coordinated with reviewers from more than a dozen electric utilities and an external peer review committee. Since 2011 it has been applied extensively to examine a range of energy and environmental policies. Models based upon US-REGEN have been developed and applied in the European Union, Taiwan, South Africa, and Mexico. Selected model publications and model documentation for the 2018 version of the US-REGEN model are available at: http://eea.epri.com/models.html.

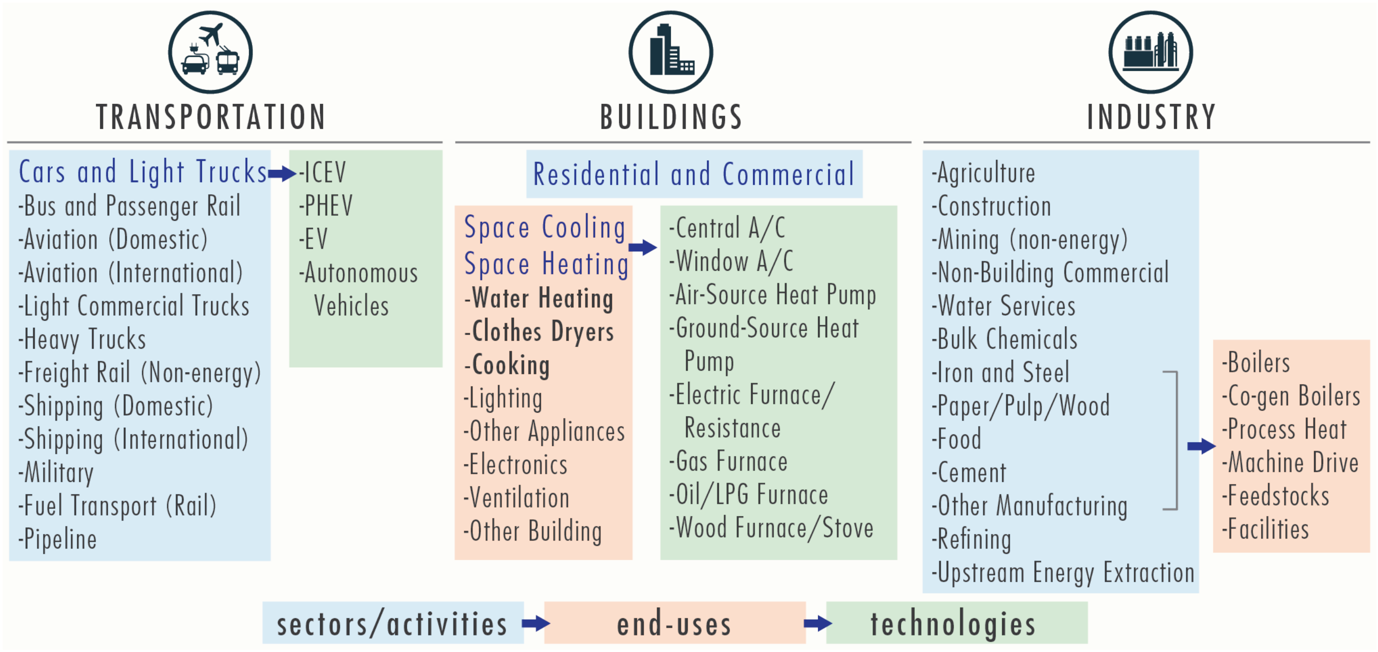
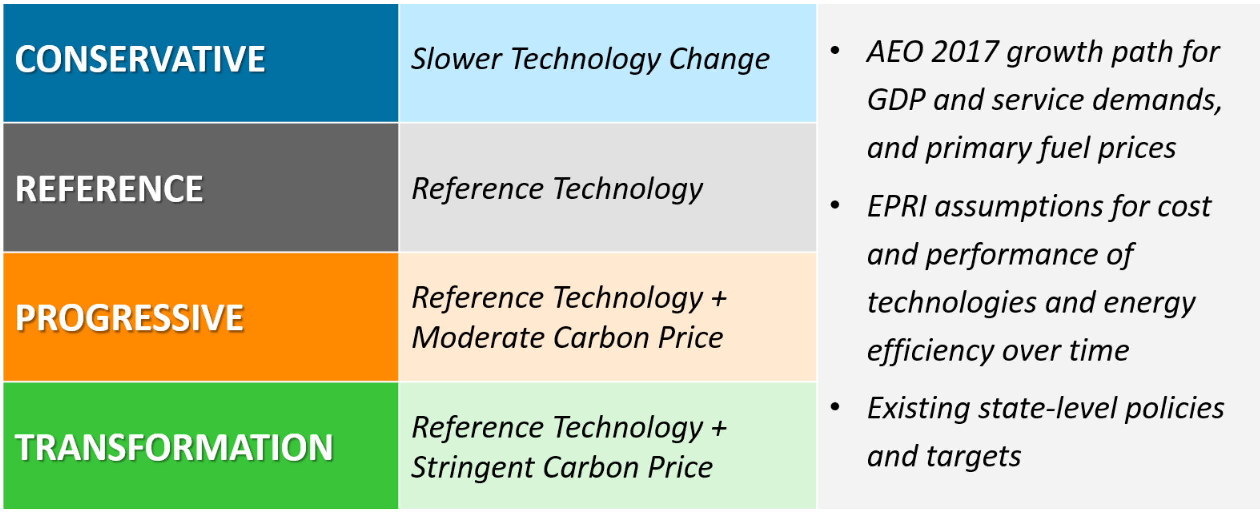


Figure 2-2. Sector/activity, end-use and technology detail in the US-REGEN end-use model. The US-REGEN end-use model consists of simple process models for end uses across the economy, along with more detailed models for understanding passenger vehicles, space heating, and cooling.

The use of US-REGEN for this study is predicated on these distinguishing features:

- Detailed disaggregation of sectors, activities, end uses, technologies (see Figure 2-2), and explicit tracking of structural classes including building type and size, building and equipment vintage, household attributes, and annual temperature profile. This detail is critical for understanding the turnover of energy-using capital, which will control the pace of technological change.
- End-use technology adoption based on economic and operational characteristics for specific applications over time (rather than exogenous assumptions about adoption rates). While many models incorporate the economic and operational characteristic of bulk electric generation technologies, US-REGEN integrates this with integrated models of end-use detail, which allows customers to respond to system changes and potentially help meet system needs.
- Synchronized hourly load profile and prices between end-use and electric sector generation mix, which means that system operational needs can be supplied either by central station or customer-side resources. In contrast, many models take a fixed estimate of customer-side resources and then optimize bulk supply of electricity.

These features enable US-REGEN to represent systematically many crucial aspects of end-use technology trade-offs omitted by other models, such as the significant heterogeneity of end-use applications and interactions of changing loads and load shapes with the electric generation sector. The model projects energy use across the economy over time, based on assumptions with respect to technology cost and performance, primary fuel prices, and policy incentives. There is considerable uncertainty with respect to these inputs. The assessment provides several scenarios and sensitivity cases, and emphasizes that results are not forecasts but rather internally consistent indicators of economic potential. Although results for this study are presented at a national level in this report, US-REGEN represents individual regions separately and regional outcomes that are quite distinct. Subsequent studies will assess electrification in more detail at the state level.



CONSERVATIVE	*Slower Technology Change*	- *AEO 2017 growth path for GDP and service demands, and primary fuel prices* - *EPRI assumptions for cost and performance of technologies and energy efficiency over time* - *Existing state-level policies and targets*
REFERENCE	*Reference Technology*	
PROGRESSIVE	*Reference Technology + Moderate Carbon Price*	
TRANSFORMATION	*Reference Technology + Stringent Carbon Price*	

Figure 2-3. Summary of U.S. National Electrification Assessment core scenarios.

Scenarios

The U.S. National Electrification Assessment examined four scenarios to consider opportunities, drivers, and challenges for electrification. ***Conservative*** and ***Reference*** scenarios focus on how changes in technology cost and performance affect outcomes. In the ***Reference*** scenario, technology costs and performance improve across the economy over time, in some cases rapidly, based on anticipated technology trends. The ***Conservative*** scenario considers a slower decline in the relative cost of electric vehicles, a key technology for electrification. Two other USNEA scenarios explore the impact of potential future economy-wide carbon policy: the ***Progressive*** scenario in which carbon is valued at \$15/ton CO_2 beginning in 2020, and the ***Transformation*** scenario in which the carbon value starts at \$50/ton CO_2 in 2020.[28] In addition, a natural gas price sensitivity analysis examined the potential impact of rising natural gas costs on efficient electrification. The scenarios are summarized in Figure 2-3.

Key Assumptions

Many assumptions underlie a detailed analysis of future electrification. This section highlights a few. A more comprehensive list of assumptions is available in the model documentation.[29]

Particularly important are assumptions about natural gas. For many end-use applications, electricity competes with natural gas, which makes the assumptions with respect to future natural gas prices important. Similarly, in many hours and regions of the United States, the price of electricity is set by the price of natural gas, which adds to the importance of these assumptions. Figure 2-4 shows two Annual Energy Outlook 2017[30] price paths used in the study. The lower price path was used for each of the four scenarios, providing natural gas, on average, for less than \$4/MMBtu through 2050. The lower gas price path was selected, in part, to raise the bar economically for switching from natural gas end uses, and hence, acting as a brake on electrification. Sensitivity analyses used the higher-price path, characterized by steady increases to reach \$6/MMBtu in 2050. The cost of natural gas for specific uses varies along these pathways, depending upon location and use.

Given the strong interest and emphasis on electrifying transportation, assumptions about vehicle cost and performance are critical. Figure 2-5 highlights assumed battery costs, a principal component of electric vehicle costs.

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28. In both the *Progressive* and *Transformation* scenarios the carbon price increases at 7% real per year through 2050.

29. US-REGEN Model Documentation, https://www.epri.com/#/pages/product/3002010956/.

30. The 2017 Annual Energy Outlook is available at: https://www.eia.gov/outlooks/aeo/pdf/0383%282017%29.pdf.

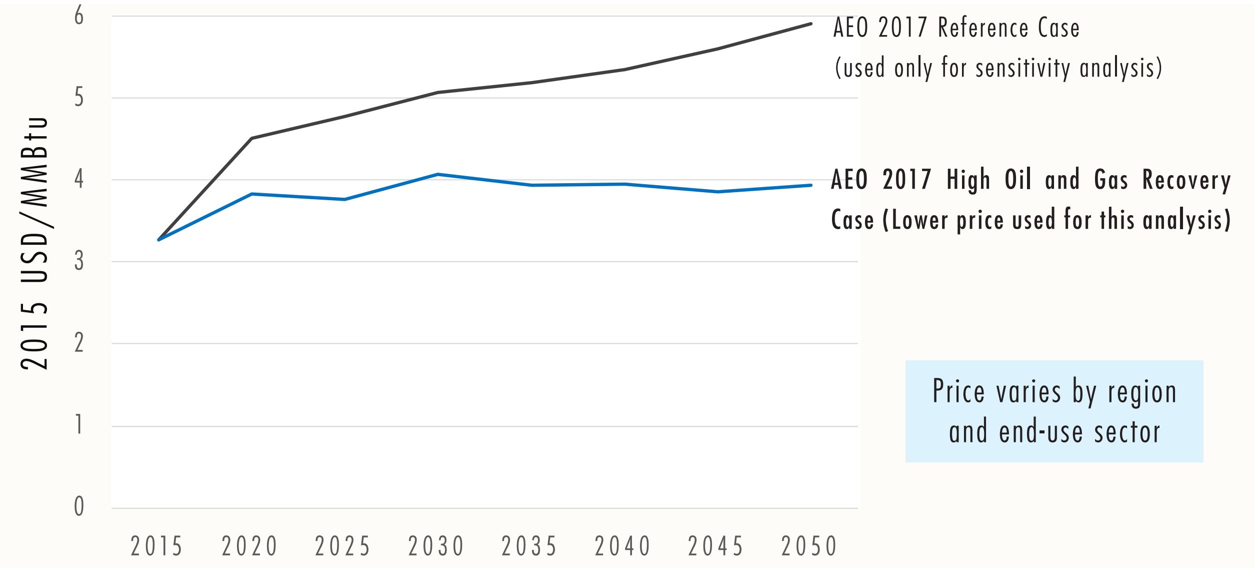

Figure 2-4. National average wholesale natural gas price paths. Natural gas price paths as projected in EIA's Annual Energy Outlook 2017. EPRI modeling is used to adjust these prices to different regions and end-use applications.

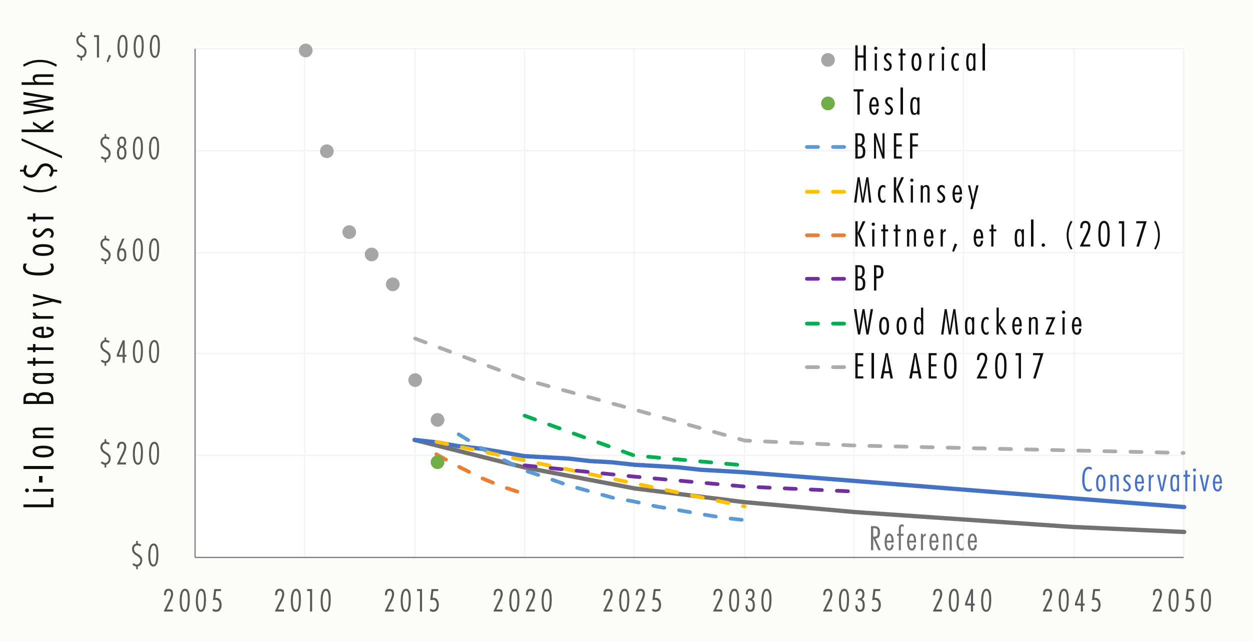

Figure 2-5. Lithium-ion battery cost assumptions, viewed in historic context and versus other selected studies. Battery costs are a principal component of EV and PHEV costs. This figure highlights assumed battery costs in the USNEA in the context of the price drops witnessed over the last few years and versus assumptions in other studies.

The purchase price of electric vehicles (EVs) is assumed to continue above that of internal combustion engine vehicles (ICEVs) through 2050 despite substantial improvements in battery technology. The purchase price of plug-in hybrids (PHEVs), though less dependent on battery costs, is assumed to drop significantly, but remain higher than that of the ICEVs through 2050 and beyond based on additional equipment necessary for dual fuel operation. The ICEV price is assumed to rise somewhat over time to pay for significant efficiency gains. Higher purchase prices of these vehicles are offset by relatively lower operating and maintenance costs (depending on vehicle use) and are discussed in Chapter 3.

All vehicles are assumed to improve their efficiency with ICEVs notably approaching 50 miles per gallon by 2050. The improved efficiency of the ICEV fleet continues the recent trend for improved efficiency and performance. This is a key component of future lower final energy use in transportation.

It is important to note assumptions regarding the cost of alternative electric generation technologies, though the generation side is not explored in detail in this report due to the demand-side focus. For all scenarios the analysis considers the same electric generation cost and performance. Figure 2-6 provides an overview of capital cost assumptions over time. The bands for each technology represent variation among the 15 US-REGEN regions. Several aspects are notable. Solar costs are assumed to drop substantially over time. Though not shown, their performance also improves. The capital costs of natural gas combined cycle (NGCC) decline as do the costs of NGCC with CCS. Combined with the low natural gas price assumption, this makes NGCC+CCS an attractive technology in scenarios with carbon constraints.

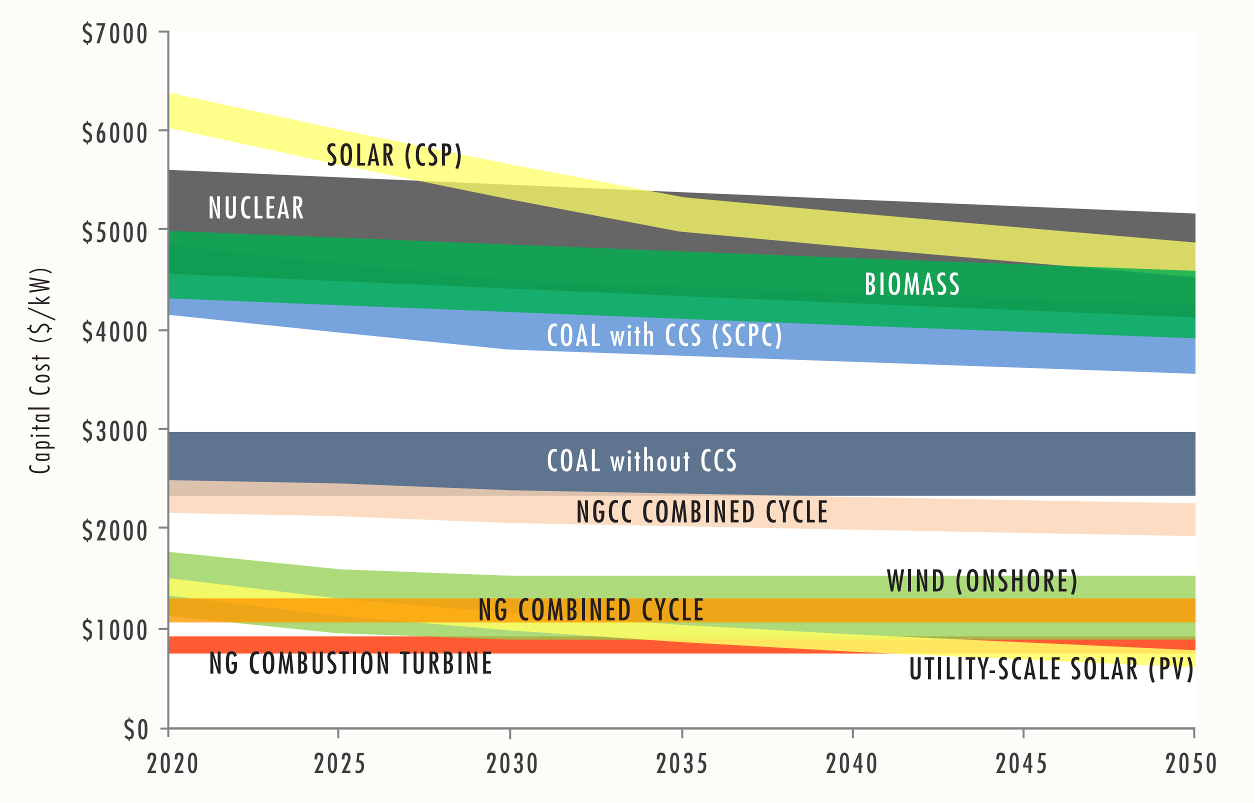

Figure 2-6. Capital costs of electric generation options.

3. MODELING INSIGHTS FROM THE USNEA–TRANSPORTATION, BUILDINGS, AND INDUSTRY

USNEA modeling results suggest that technological change and policy incentives could drive significant changes to the U.S. energy system related to electrification as well as other factors. This chapter presents key insights gained for each major end-use sector: transport, buildings, and industry. Chapter 4 aggregates these results to provide economy-wide insights.

Transportation

Light-Duty Transport

The transportation sector, especially light-duty cars and trucks but other segments as well, represents the single largest opportunity for efficient electrification. Over 40% of final energy in the United States is used for transportation, and nearly two-thirds of that (a quarter of U.S. total final energy) is consumed as liquid fuels for light-duty passenger vehicles. Electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) have improved rapidly in recent years, and while they reflect only a small portion of new sales currently, they appear to be on the cusp of much wider market adoption. With continued declines in battery costs, as well as new model designs and more widespread availability, EVs and PHEVs will soon become cost-effective alternatives to conventional internal combustion engine vehicles (ICEVs). Their slightly higher purchase price, charging equipment costs, and occasional range limitations, will be more than offset by lower operating costs, in terms of both fuel and maintenance, for most drivers. Figure 3-1 compares assumed annualized costs of an EV with an ICEV over time for a representative driver in the *Reference* scenario. Initially, there are cost premiums associated with limited EV availability in some market segments. As these premiums fall, the savings in operating costs dominate, and total costs of the EV fall below the ICEV. Because operating costs (fuel and maintenance) are higher for vehicles driven more, total EV costs fall below those of the ICEV sooner for high driving intensity consumers. The US-REGEN model projects adoption based on these relative total costs, subject to an assumed lag in consumer responsiveness to changing economics. If the total costs of an EV and ICEV are the same, the model will, after a few years, project equal adoption. As the total cost of EVs falls progressively further below that of ICEVs, the model projects a greater and greater share for EVs.

FINDINGS IN BRIEF—TRANSPORTATION

*In the **Reference** scenario, light-duty electric and plug-in electric vehicles are projected to comprise 75% of new vehicle sales and 70% of vehicle miles traveled by 2050, compared to essentially zero today. This shift, combined with large efficiency improvements in internal combustion engines, leads to a 60% drop by 2050 in final energy use for light-duty vehicles despite an assumed increase in vehicle miles traveled of almost 30%.*

- *Although the purchase price of EVs and PHEVs are assumed to remain somewhat higher than ICEVs through 2050 in the **Reference**, lower fuel and maintenance costs drive total costs of EVs below that of ICEVs in the early 2020s for people who drive 18,000 miles annually (50% more than average).*
- *Adoption of electric vehicles is slower and lower in the **Conservative** scenario, which assumes slower reductions in electric vehicle costs (e.g., lower availability, slower improvement in batteries) and more rapid improvement in ICEVs. Electric vehicles provide 50% of VMTs in this scenario.*

*For rail, trucks, and buses, the **Reference** scenario projects the electric share of final energy to grow from 1% today to 40% by 2050, as high utilization and operational cost savings outweigh higher upfront costs. Electricity is not projected to make inroads in maritime or aviation.*

*The carbon price path assumed in the **Transformation** case causes only a marginal increase in transportation electrification. For light-duty vehicles, fuel costs are a fraction of overall costs, and even a $100/ton price on CO_2 emissions raises the gasoline price by less than $1/gallon.*

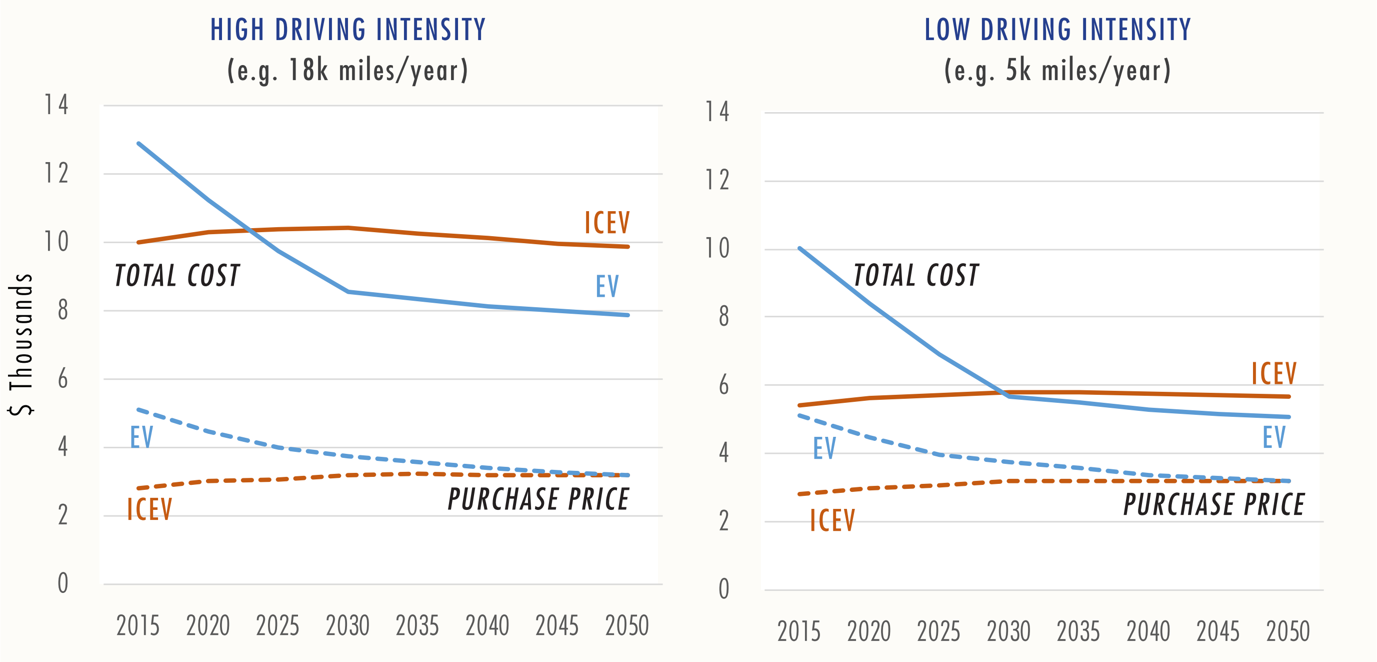

Figure 3-1. Annualized costs (in $1000) of light-duty vehicles for two representative consumers in Reference scenario (based on suburban NE-Central model region).

Based on EPRI assumptions about future vehicle cost and performance and modeling structural characteristics of household vehicle service demands, the ***Reference*** scenario projects that by 2030 electricity will power approximately a quarter of vehicle miles traveled (VMTs), rising to 70% by 2050. This level of electrification means that EVs and PHEVs reach around 40% of new vehicle sales by 2030, and around 75% by 2050. Combined with efficiency improvements in all vehicles, this leads to rapidly declining final energy use in the light duty vehicle sector.

Figure 3-2a shows the demand for electricity and liquid fuels corresponding to the service demand projection, including a decomposition of the decline into the effects of efficiency improvements and electrification. This formulation will be used across other sectors and in aggregate to communicate the magnitude of each effect. Even with no electrification of passenger vehicles, final energy would decline based on improved ICEV efficiency (including an assumed trend of more hybrid-electric drivetrains, without a plug). The shift to EVs decreases final energy further because of the much greater "tank-to-wheels" efficiency of the electric drive-train.

This rapid rate of market penetration in the ***Reference*** scenario is supported by EPRI's assessment of the economic potential for EVs and PHEVs and by recent trends in technology costs, yet the projection is not a forecast: neither the technological progress nor the consumer behavior underlying the modeling is a certainty. In the ***Conservative*** scenario (Figure 3-2b), cost declines for EVs and PHEVs occur more slowly than expected and the ICEV technology achieves greater cost/performance gains. The electrification trend remains in this case but deep market penetration is delayed, with the projected share of electrified VMTs reaching only 12% by 2030 and just over 50% by 2050. This scenario depicts persistent economic headwinds to vehicle electrification based on technological progress favoring ICEVs. A similar scenario could be derived based on behavioral factors, such as information gaps and risk aversion.

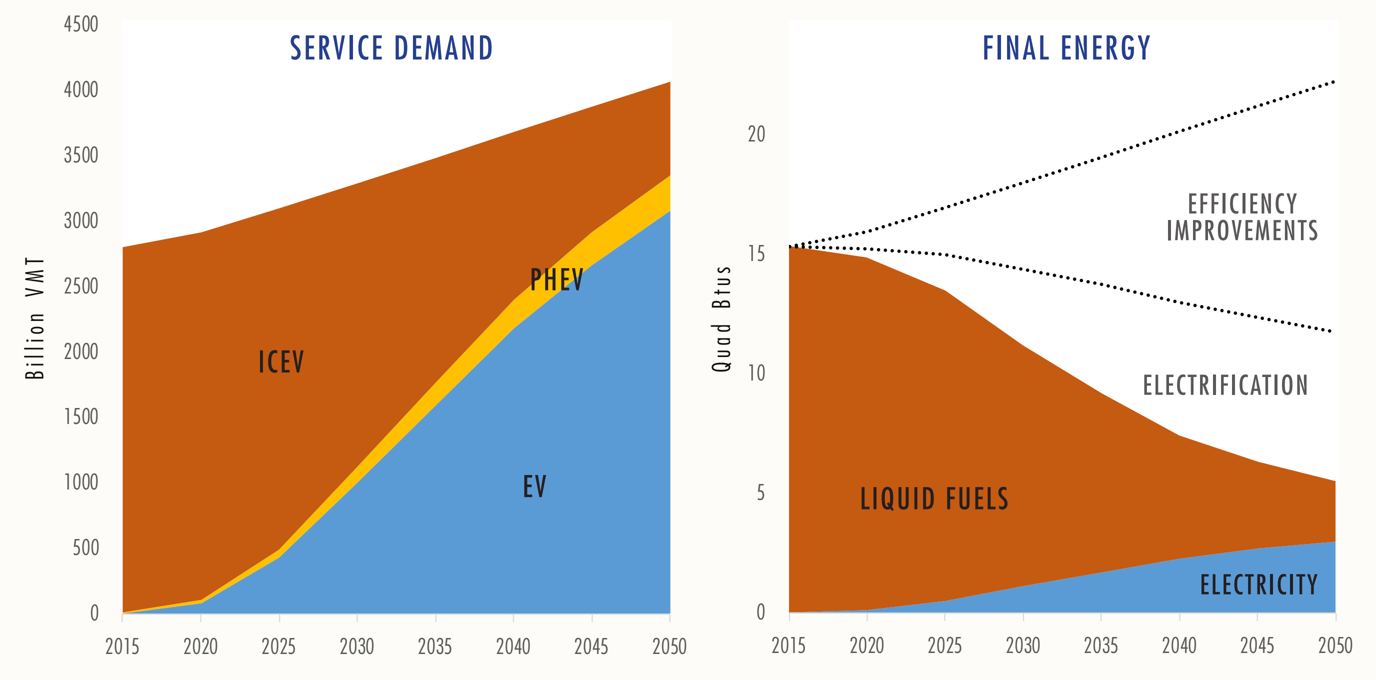

Figure 3-2a. Reference scenario projections for light-duty vehicle service demand (left) and final energy use (right).

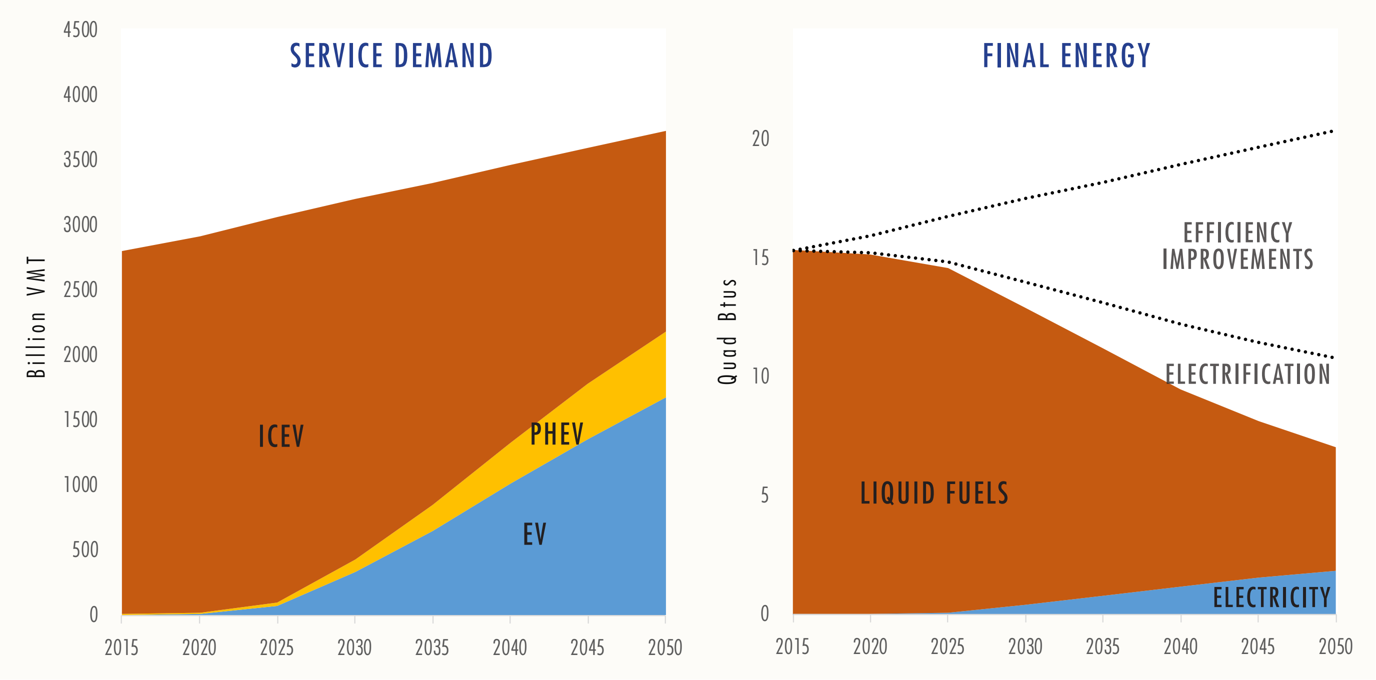

Figure 3-2b. Conservative scenario projections for light-duty vehicle service demand (left) and final energy use (right).

Heavy Transport

Battery-based technology is also emerging as a viable alternative for heavy transport segments, including transit buses and rail, commercial trucks, and long-distance freight trucks. Together these segments comprise about 10% of total U.S. final energy today. As with light-duty vehicles, higher up-front costs are offset by lower operating costs. Although the incremental cost of the vehicle is greater due to larger battery requirements, heavy-duty vehicles typically have much higher utilization factors than light duty, indicating greater savings on operating costs in an industry that pays attention to total costs. A key driver for market share of these vehicles will be customer expectations regarding the future price of diesel and natural gas-powered alternatives; continued low prices make a move to electric more challenging.

In the ***Reference*** scenario projection, electricity's share of service demand across these categories grows from approximately 1% today (primarily in transit rail) to nearly 40% by 2050. Other heavy transport such as aviation and maritime shipping are not currently prospects for electrification, but these activities represent less than 7% of U.S. final energy. Figure 3-3 shows the ***Reference*** scenario projections for final energy in both the heavy-duty surface transport category and the other heavy-duty category. Overall, final use of non-electric fuels in the transportation sector, due to both efficiency improvements and substantial electrification, falls by nearly 60% between 2015 and 2050 in the ***Reference*** scenario, and the electric share of total transportation final energy rises to 25%.

In the ***Progressive*** and ***Transformation*** scenarios, these trends accelerate, but only slightly. A carbon price has a comparatively small effect on the transportation sector, partly because the incumbent fossil fuel (petroleum) is relatively expensive, and partly because energy is a relatively small part of total service cost. Thus, the abatement cost curve is steep for additional emissions reductions beyond the ***Reference*** case. Electrification of transport is driven much more by technical change than by an explicit carbon policy.

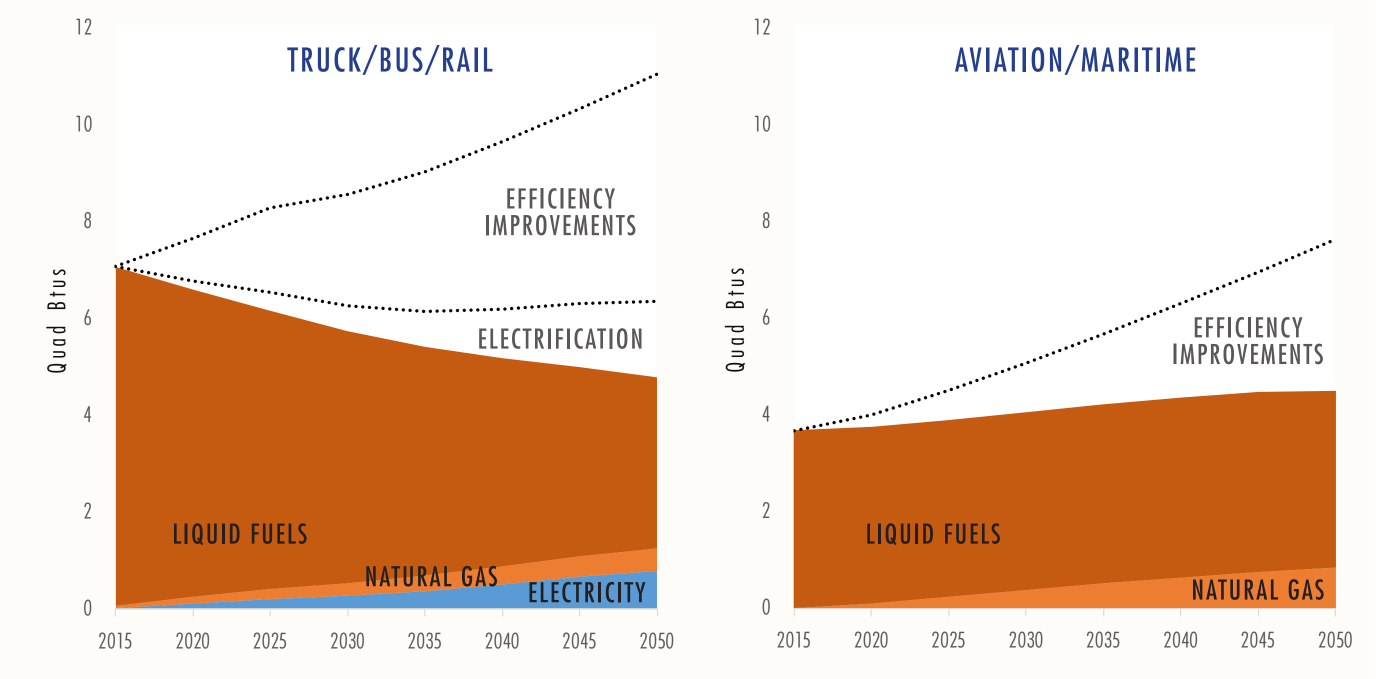

Figure 3-3. Reference scenario projections for final energy use in heavy-duty transport.

Buildings

Residential and commercial buildings today account for 30% of U.S. final energy, roughly half of which is consumed as electricity.

Space Heating

After passenger vehicles, building space heating is the next largest single end-use application in terms of final energy consumption, at 12% of the total. Heat pump technology represents an expanding opportunity for efficient electrification. Currently electric heat pumps are the main heating source for approximately 15% of residential space heating, and around 9% of commercial space heating. Additionally, electric resistance is used for around 19% of residential space heating and 17% of commercial space heating. Electric heating is used most commonly in regions with milder climates and relatively low retail electricity prices.

Expected future efficiency improvements in heat pump technology could increase market share substantially, even in colder climates. Figure 3-4 shows the impact of changing technology and relative fuel prices on air-source heat pump economics. Because heat pump efficiency and capacity falls in lower temperatures, their energy efficiency relative to natural gas furnaces, ranges from approximately 1.5 times as efficient in a particularly cold region to more than 3 times as efficient in a warmer region. Comparing costs, electricity ranges anywhere from 2 times to 5 times as expensive as natural gas on a Btu basis (assuming current residential and commercial rate structures).[31] Regions having lower electricity price ratios and higher efficiency ratios can be expected to have an economic advantage and indeed are those where heat pumps are currently deployed. Figure 3-4 shows that as heat pumps become more efficient in the *Reference* scenario, additional locations realize economic benefits from deployment,

FINDINGS IN BRIEF—BUILDINGS

*In the **Reference** scenario, the square footage heated primarily by electric heat pumps is projected to expand from 15% of total square footage today to 50% by 2050. However, the change in energy use is less pronounced because much of this expansion is in warmer climates.*

- *Heat pumps today are economically attractive in warmer regions with relatively low retail electricity prices. With projected improvements in heat pump efficiency—especially at colder temperatures—and changes in relative gas and electricity prices, heat pumps become economically attractive in more locations.*
- *Demand for space heating is assumed to rise 50% by 2050, with most growth in warmer climates (from AEO 2017). Heat pumps supply heat for much of this growth in square footage. The square footage heated by natural gas is projected to remain essentially constant over time.*
- *Despite the assumed 50% growth in heating demand (AEO 2017), energy consumed by heating drops 20% by 2050 driven by efficiency improvements, a shift from electric resistance heating to electric heat pumps, and efficient electrification.*
- *The carbon policies assumed in the **Progressive** and **Transformation** scenarios increase the relative price of gas to electricity, causing a stronger shift toward electric heat pumps as a primary source of heat, often combined with a natural gas backup in colder climates.*

Heat pump water heaters—which for perspective, account today for one-third as much final energy use as space heat—are projected to have similar gains to electric heat pumps.

- *Service demand for water heat is assumed to grow by one-third by 2050 (AEO 2017). Heat pump water heaters are projected to account for most of this growth, with consequent significant reductions in final energy use.*

*In the **Reference** scenario, electricity use for electric-dominated end uses—lighting, cooling, ventilation, appliances, and electronics—is projected to decline 20% by 2050, despite an assumed 50% increase in demand for their services. These declines are driven by assumed gains in efficiency.*

- *In 2015 these loads comprised 50% of all electricity use. They are projected to contribute only 30% of electricity demand in 2050.*

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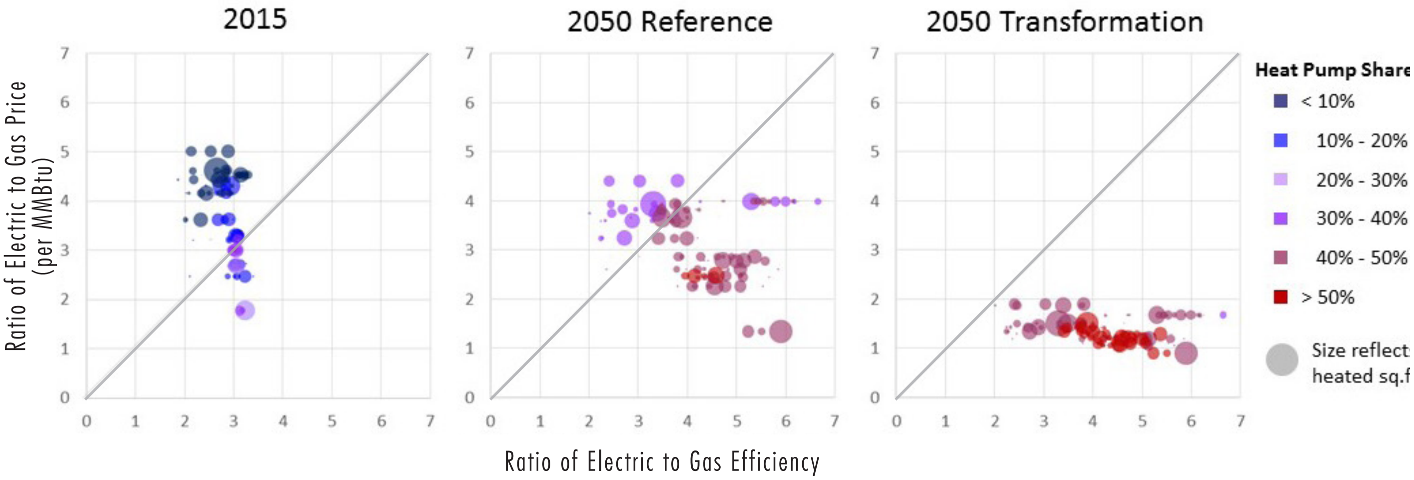
[31] Note that rate structures designed to reduce electricity consumption can make heat pumps economically unattractive in regions where they are otherwise attractive based on performance and efficiency. In future projections, these rate structures are assumed to remain unchanged, even though rate design changes could lead to lower costs to customers and lower emissions.



Currently heat pumps are cost-effective only in certain regions with both favorable climate and relative prices

With performance improvements, and rising relative gas prices, especially with carbon pricing, heat pumps become more competitive in more regions over time

Figure 3-4. Changing heat pump economics across regions, climate zones, and scenarios. The horizontal axis refers to heat pump efficiency relative to a gas furnace; the vertical axis refers to residential customer price of electricity relative to natural gas (on a Btu basis). Individual dots represent distinct climate zones within model regions. A dot below the 45-degree line indicates locations with lower operating costs for a heat pump (i.e., where the heat pump's higher efficiency outweighs the electricity price premium).

and their adoption increases. In the ***Transformation*** scenario, carbon pricing lowers the price of electricity relative to natural gas, leading to even greater economic advantage.

Even so, these projections do not imply full electrification of space heating in all buildings. The modeling projects a potentially economically efficient role for natural gas as a backup fuel for heat pumps systems. In all but the mildest climates, heat pumps are paired with a back-up heat source because their performance drops at lower temperatures. While today the predominant back-up source is electric resistance heat (especially in warmer climates), as heat pump technology improves it expands into colder regions, where natural gas back-up is more cost effective. Figure 3-5a shows the ***Reference*** scenario projection for the technology and energy mix in residential space heating. The share of space primarily heated by electricity rises from approximately one-third currently to two-thirds by 2050, while final energy declines. Again, the decline reflects both the effects of efficiency improvements and electrification, along with structural effects of faster growth in heating demand in warmer climates (based on input assumptions derived from population and economic growth). Despite this trend, natural gas use for space heating barely declines, based in part on the offsetting decline in other (predominantly petroleum) non-electric fuels, and due to its increased use to fuel back-up for heat pumps. As seen in the figure, more than half the area heated by heat pumps is served by a non-electric backup technology.

With an assumed carbon price in the ***Transformation*** scenario, direct use of natural gas in buildings declines as heat pumps gain a larger share of heating (see Figure 3-5b). As noted later, an increase in the use of natural gas with CCS to generate electricity in the ***Transformation*** scenario causes overall gas use to increase from current levels.

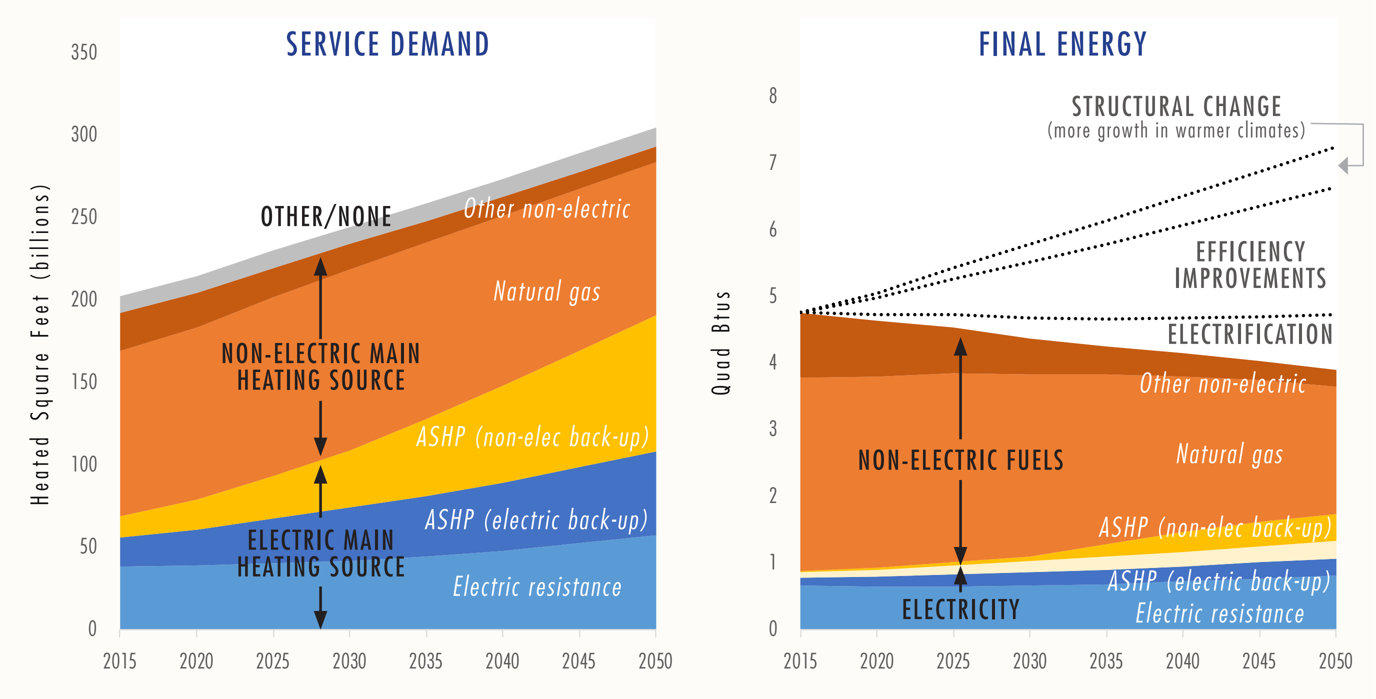


Figure 3-5a. Reference scenario projections for residential space heating service demand (left) and final energy use (right).

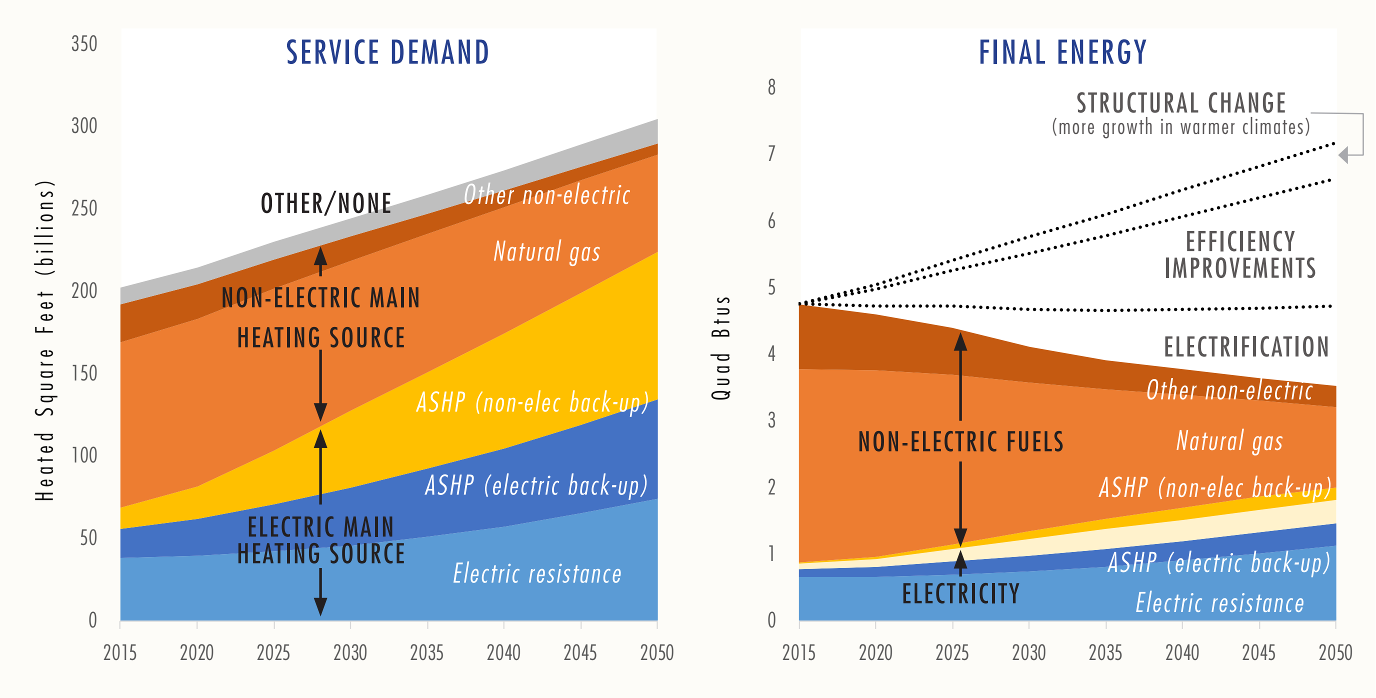


Figure 3-5b. Transformation scenario projections for residential space heating service demand (left) and final energy use (right).

Water Heating

Heat pump technology also plays an expanded role in water heating, although this use constitutes only around 4% of total final energy. Approximately 43% of homes currently use electricity for water heating, although only a small fraction of these use heat pump water heaters, which today are much more efficient but more expensive than conventional electric resistance water heaters. As costs of heat pump water heaters decline over time, the ***Reference*** scenario projects a growing role for them, with more than half of residential customers using electricity for water heating (Figure 3-6a). In the ***Transformation*** scenario, the economic advantage of electricity increases, leading to approximately 60% of residences served by electric water heating (Figure 3-6b). Nonetheless, because the more efficient heat pump water heating technology displaces electric resistance as well as natural gas and other non-electric fuels, the net impacts on electricity demand are minor. Both total and electric final energy for residential water heating remain roughly flat over time despite growing housing stock.

Electric-only End Uses

Nearly half of today's total electricity demand is used for building services for which electricity is the dominant energy option. The services include cooling, appliances such as refrigerators and dishwashers (excluding dual-fuel appliances such as cooking stoves and clothes dryers), electronics, lighting, and ventilation. Demand for these services is projected to grow, particularly for residential and commercial electronics, but efficiency improvements are projected to outweigh service demand growth. Historically, these efficiency improvements have come from government standards or have been accelerated by efficiency program efforts. More recently, advances have also come from what is often called the third wave of energy efficiency—technology spillover from dramatic efficiency improvements in consumer electronics. The result is that electricity used for each of these services is projected to decline (with the exception of ventilation and miscellaneous electric loads), so that by 2050 in aggregate they comprise less than 30% of total electric load (Figure 3-7).

It is important to note, in conclusion, that even in the ***Transformation*** scenario, more than 50% of building final energy use in 2050 is projected to be non-electric, predominantly supplied by natural gas. For economy-wide emissions, this scenario resulted in just under a 70% reduction relative to 2015. If more stringent reductions were desired, electricity would play a still greater role in buildings.[32]

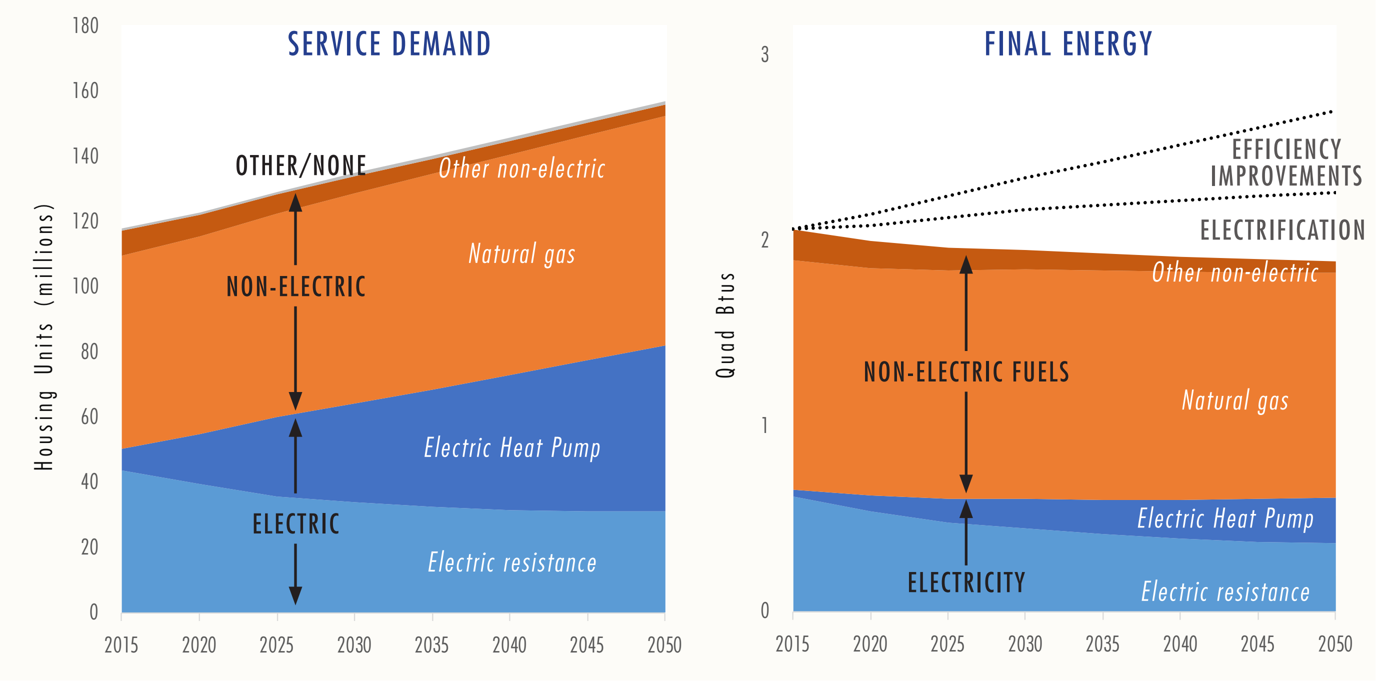


Figure 3-6a. Reference scenario projections for residential water heating service demand (left) and final energy use (right).

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[32] There remain questions about how far electrification of buildings can or should go economically. Answers most likely will differ by locale, available energy resources, and by the building use. For example, a recent study for the University of California system examined the potential for electrification to achieve their decarbonization goal, https://www.nceas.ucsb.edu/files/research/projects/UC-TomKat-Replacing-Natural-Gas-Report_2018.pdf.

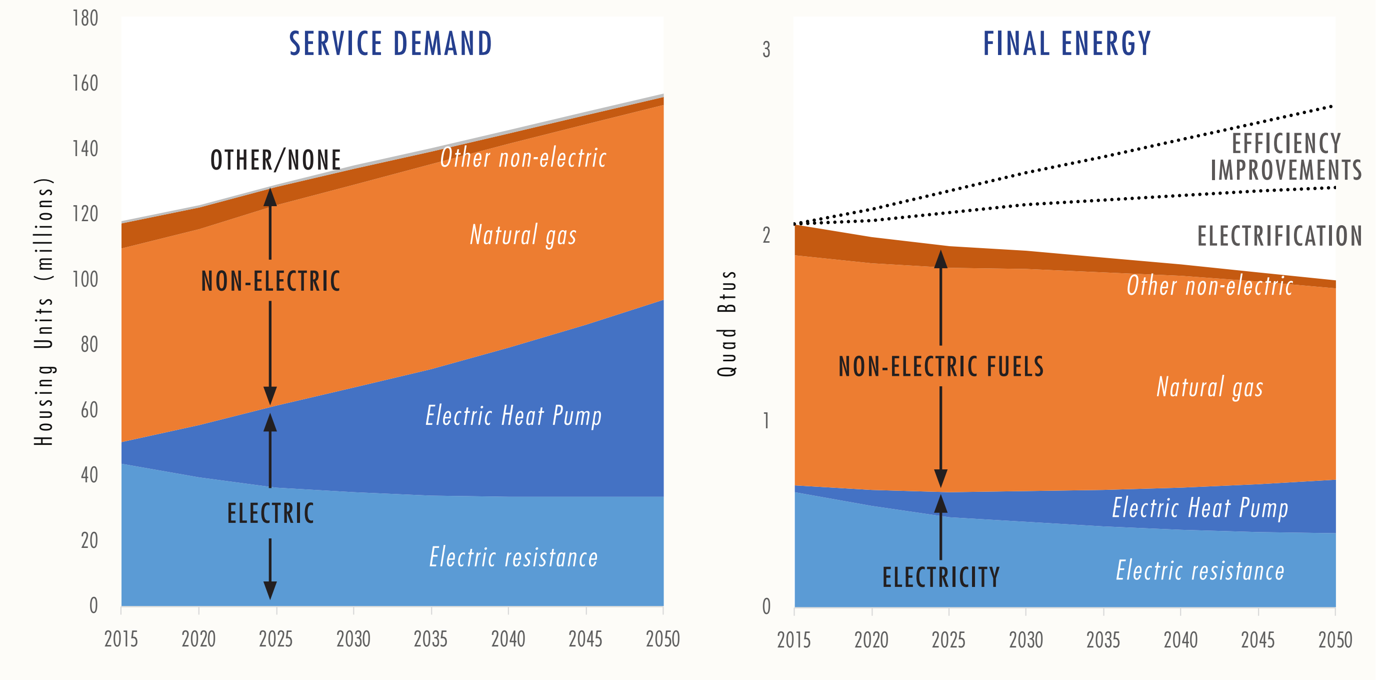

Figure 3-6b. Transformation scenario projections for residential water heating service demand (left) and final energy use (right).

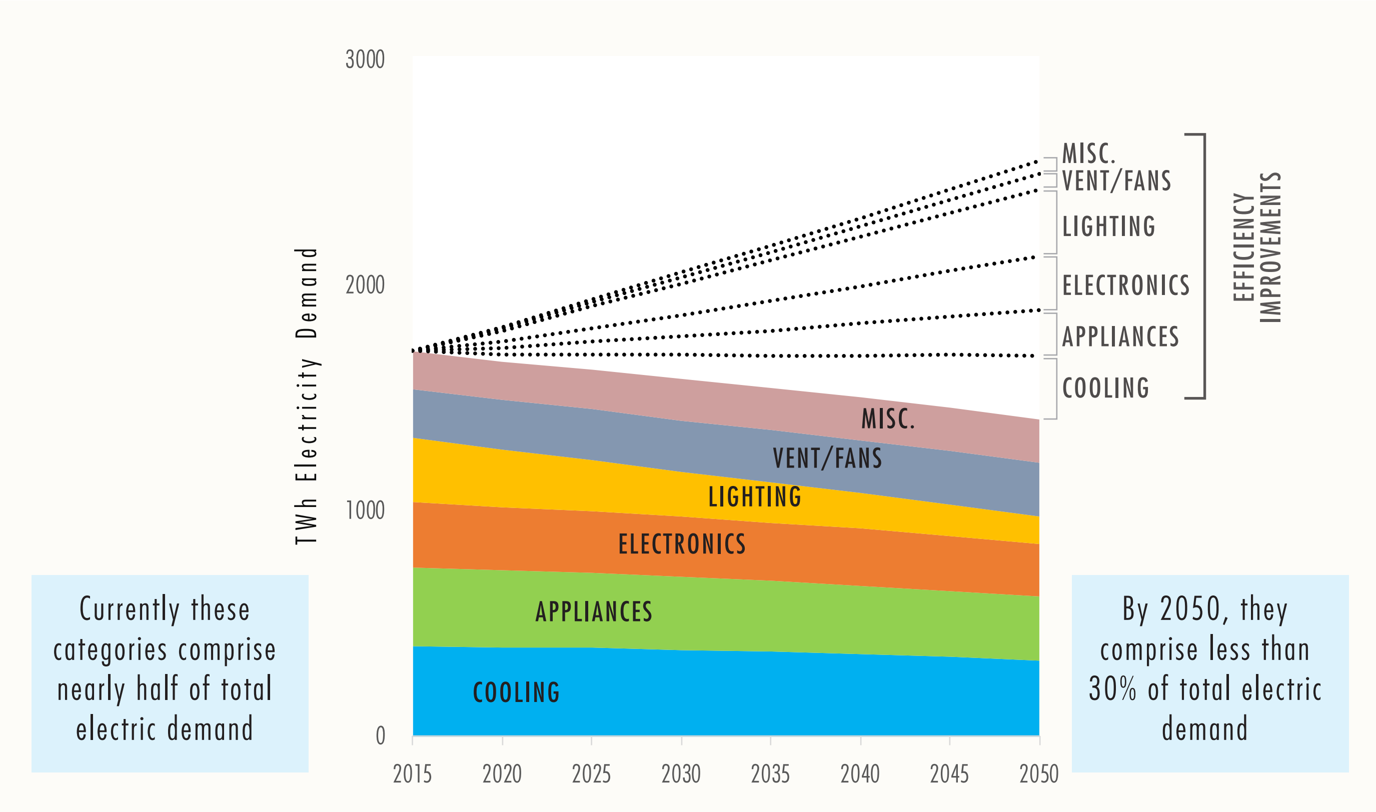

Figure 3-7. Reference scenario projections for efficiency improvements vs. service demand growth in electric-only building uses.

FINDINGS IN BRIEF—INDUSTRY

U.S. industry uses energy for diverse needs and purposes, including activities as disparate as manufacturing, mining, and farming. For this analysis, modeling employed more aggregate methods and data than were used in the transportation and building analyses.

*The **Reference** scenario projects significant efficiency improvements in industry and limited electrification. Natural gas use grows, partially displacing petroleum use in both manufacturing and other industries.*

*In the **Transformation** scenario, electricity becomes relatively cheaper than other fuels and is substituted for both natural gas and petroleum in some uses.*

Industry

Industrial activities account for 30% of final energy in the United States, primarily manufacturing, along with agriculture, construction, and mining. Industrial energy services include boilers for steam production and in some cases co-generation of electricity; process energy, including heating, cooling, and machine drive; and non-process uses such as facilities and non-road vehicles. Opportunities exist for fuel-switching in all of these as technologies change and relative fuel prices shift.

Process heating with emerging electric technologies such as induction melting and infrared drying can yield improved product quality and capital productivity. In addition to being economic, these technologies can improve productivity by enabling faster operation and improve workplace safety.

As battery technology improves, non-road vehicles may be viable for electrification, especially where indoor air quality is an issue. The wide-ranging benefits of a number of these technologies, such as electric forklifts, was discussed in Chapter 1.

At the same time, low natural gas prices will increase the incentive to shift to natural gas use from other non-electric fuels in various process applications. Electric technologies today face limits in supply high-temperature water, for example. Natural gas is projected to substitute for petroleum in some applications.

However, the heterogeneity of applications and individual processes makes comprehensive modeling of the industrial sector difficult. US-REGEN has adopted a more top-down approach than the technology-rich formulations in the transportation and buildings sectors, with parameters calibrated to available data. The ***Reference*** scenario projections suggest that while industrial sector electric demand will continue to grow, based on assumptions of robust economic growth in U.S. manufacturing sectors (see AEO 2017), the shifts to electricity are relatively limited (Figure 3-8a). In the *Transformation* scenario, carbon incentives sufficiently change the relative economics and put a premium on electrification in industry, driving down direct consumption of fossil fuels and contributing additional electricity demand (Figure 3-8b).

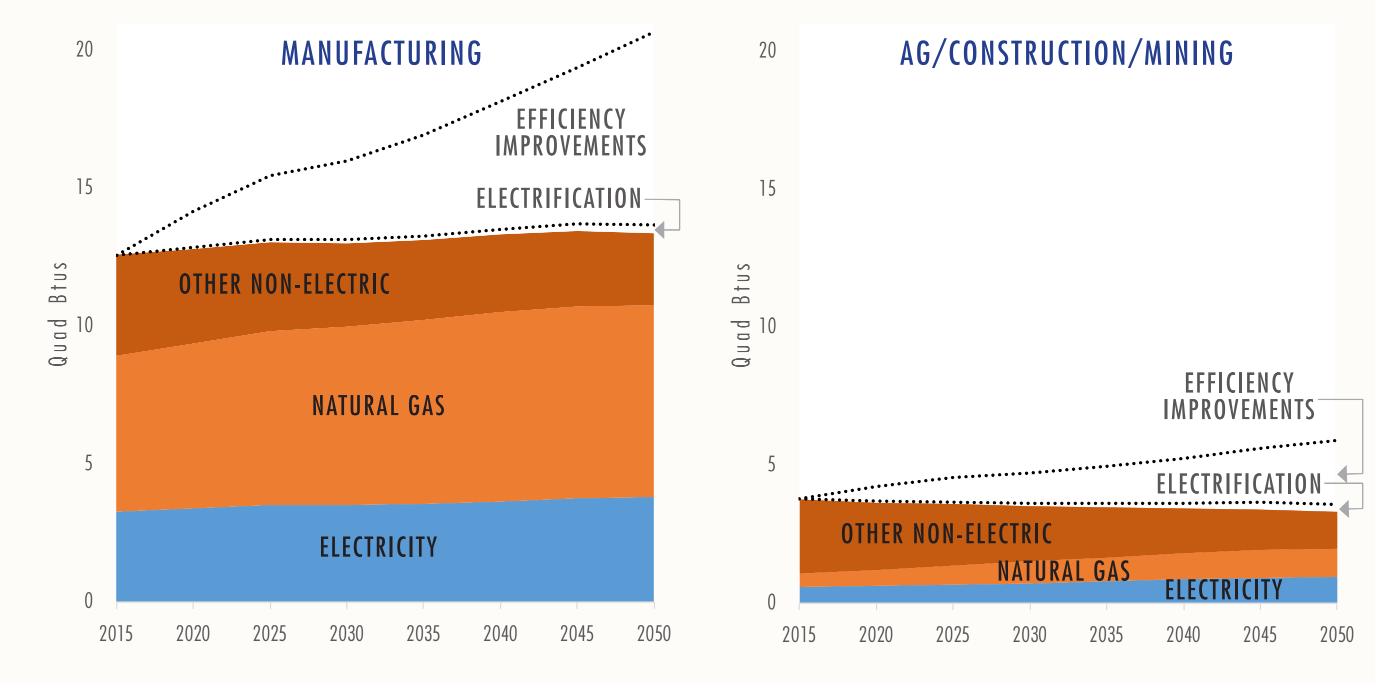

Figure 3-8a. Reference scenario projections for industry final energy use in manufacturing (left) and non-manufacturing (agriculture, construction, and mining sectors [right]).

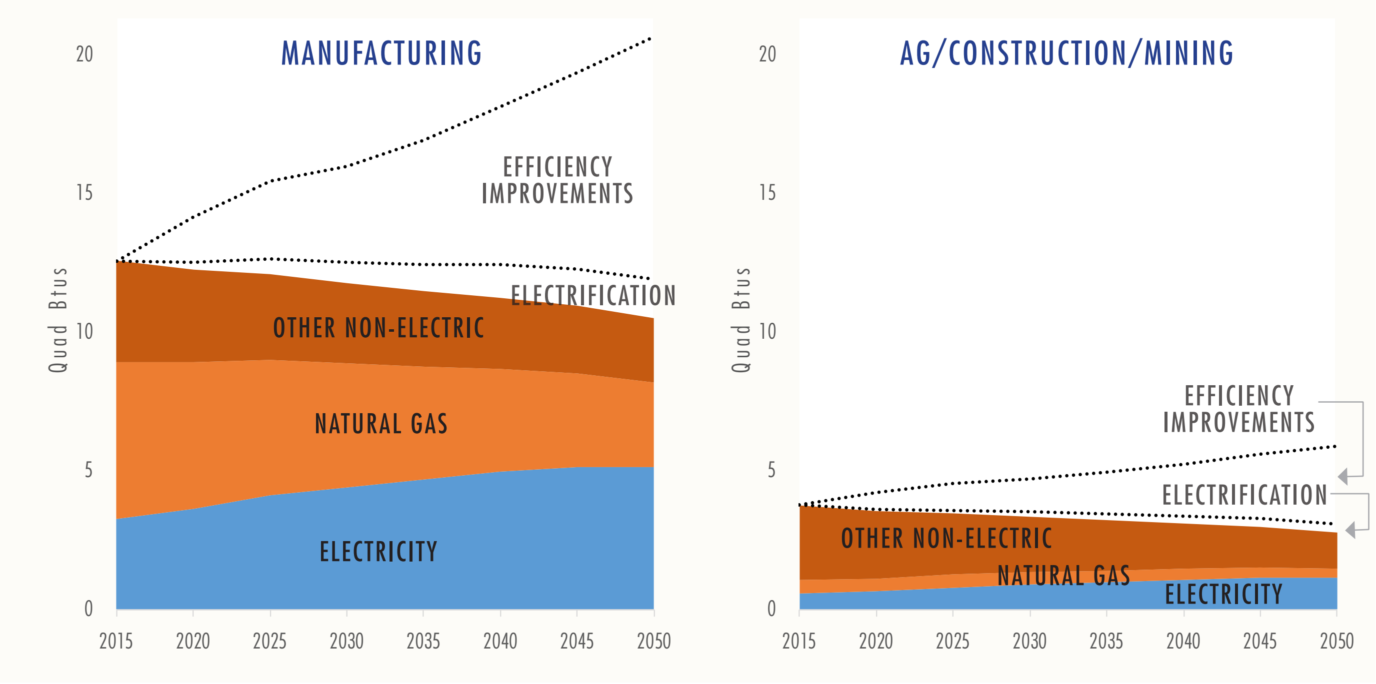

Figure 3-8b. Transformation scenario projections for industry final energy use in manufacturing (left) and non-manufacturing (agriculture, construction, and mining sectors [right]).

KEY FINDINGS—CUSTOMERS INCREASE RELIANCE ON ELECTRIC END USES

In the United States, electricity has grown from 3% of final energy in 1950 to approximately 21% today. Across the four scenarios, electricity's role continues to grow, ranging from 32% to 47% of final energy in 2050. Providing an array of benefits to customers, this trend also has important implications for how the electric system will evolve.

Without efficient electrification, EPRI projects that electric loads will decline, driven by efficiency gains. With efficient electrification, the study projects cumulative load growth of 24–52% by 2050. The 52% load increase projected in the ***Transformation*** *scenario implies a 1.2% annual growth rate. While some of this load growth will be customer-supplied, capacity to ensure reliability will, in most cases, be supplied by the utility. By comparison, annual load growth from 1990–2000 was 2.7%, dropping to 0.82%, on average from 2000–2010. For electric companies, such slow but steady growth can moderate potential rate impacts of grid modernization investment.*

In all four scenarios, growth is driven by the transportation sector, starting from minimal electric use today. Electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) quickly become cost-effective alternatives to conventional vehicles for most drivers. Heat pumps for space and water heating, along with electric technologies in industry and heavy transportation, are increasingly adopted in favorable markets, at rates constrained by stock turnover.

The analysis suggests that the economic potential for electrification is compelling in many applications, yet realizing this potential requires removing policy and regulatory barriers that impact choice or limit supporting infrastructure. For customers, other barriers include a lack of innovative financing or risk aversion stemming from insufficient information on electrification technologies' value and benefits.

4. MODELING INSIGHTS FROM THE USNEA–ECONOMY-WIDE

Chapter 4 presents the economy-wide insights from the assessment. This broader perspective on the modeling results ties together sectoral insights presented in Chapter 3 and elaborates on key findings introduced in the Executive Summary.

In the United States, electricity has grown from 3% of final energy in 1950 to approximately 21% today. Nearly all electricity is currently used in the buildings and industry sectors, while its share in transportation is virtually zero (Figure 4-1). Efficient electrification in the ***Reference*** scenario is dominated by transport. In this scenario, buildings and industry continue to move slowly, but steadily, toward electric end uses. The carbon price assumed in the ***Transformation*** scenario has a marginal impact on transport, but drives substantial additional electrification in both buildings and industry.

Over that same period final energy use has generally increased, although both electricity and total energy demand have slowed recently due to a combination of structural change (different growth rates across different parts of the economy) and gains in energy efficiency (Figure 4-2). For all four USNEA scenarios, final energy is projected to decline, while electricity demand, and its share of total final energy, are projected to rise. By comparison, the EIA's Annual Energy Outlook (AEO, 2017) projects rising final energy with little change in the share of electricity.

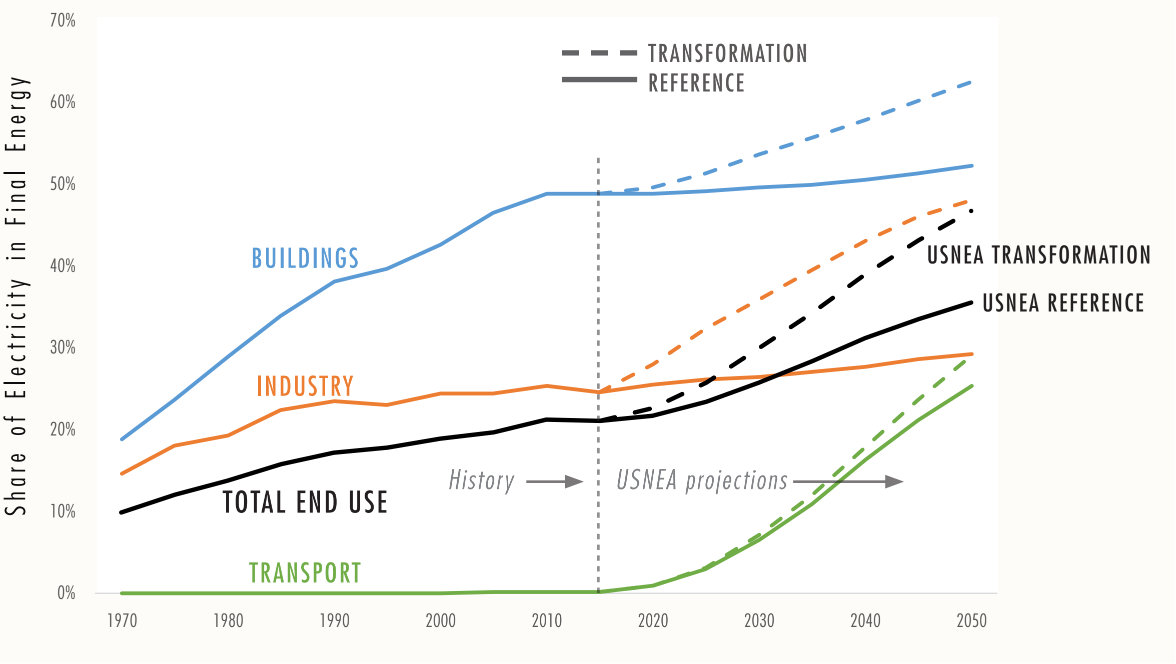

Figure 4-1. Share of electricity in final energy across sectors. *Electricity's share rises from 21% today to 36% in the Reference scenario projections, driven by transportation. The share rises substantially in all sectors in the Transformation scenario projections.*

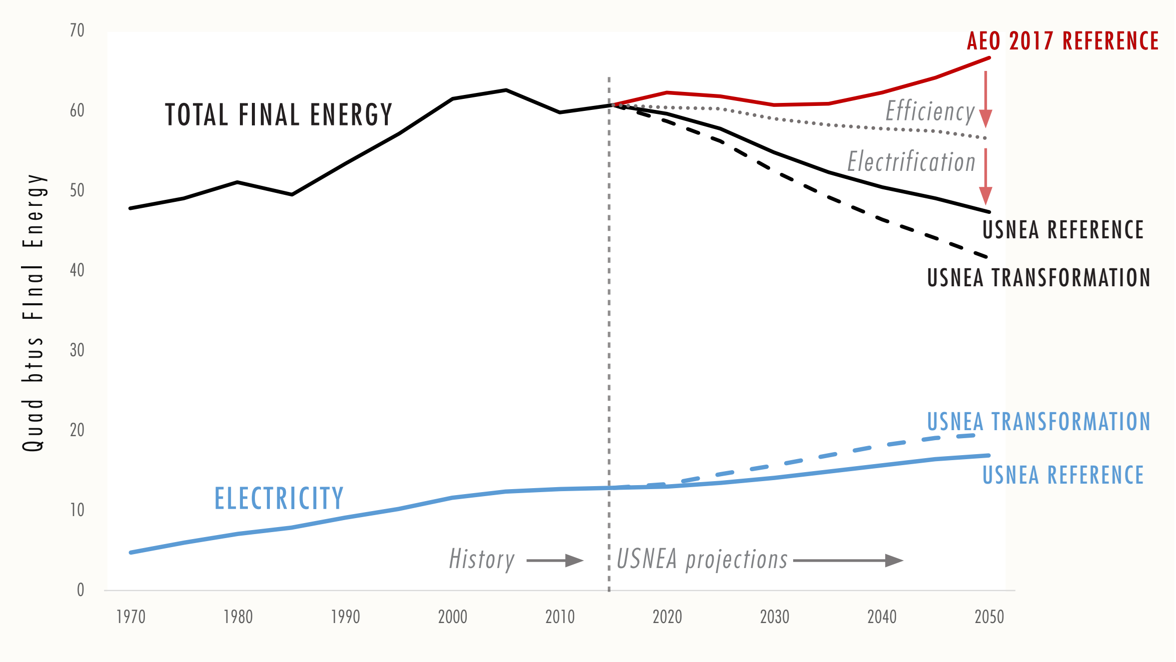

Figure 4-2. U.S. total and electric final energy. *Final energy declines while electricity demand rises in the Reference scenario projections, with both more efficiency improvements and more electrification than in the AEO projections. Both efficiency and electrification accelerate in the Transformation scenario projections.*

KEY FINDINGS—FINAL ENERGY CONSUMPTION DECREASES

The modern era has been driven by a significant and continuing growth in final energy—a measure of energy consumed across all fuel types at the end use. Most analyses suggest continued growth for decades to come.[33] In contrast, all four USNEA scenarios project falling final energy consumption. Continued growth in economic activity and energy services across all sectors of the economy is offset by efficiency improvements across the energy system, led by advances in individual end uses, such as lighting, variable speed motors, and more efficient internal combustion engine vehicles, as well as a shift from non-electric to more efficient electric technologies.[34] For the ***Reference*** *scenario, the analysis projects a reduction in economy-wide final energy consumption of 22% by 2050, while electricity use grows by 32%. Final energy consumption declines further, and electricity use grows more in the* ***Progressive*** *and* ***Transformation*** *scenarios. This fundamental reconfiguration of the energy system, which occurs in the Reference scenario and even in the* ***Conservative*** *scenario, illustrates the importance of establishing policies and regulations that adopt an economy-wide perspective of energy efficiency.*

The projected decline in final energy demand occurs despite assumed growth in the economy and demand for energy services. This result is explained by three effects, shown separately on the left panel of Figure 4-3a. First is the effect of structural change—an assumption derived from AEO 2017—through which service demands such as vehicle miles traveled, building space (to be heated, cooled, and illuminated), and industrial output grow more slowly than the economy as a whole. The second effect reflects technological changes that reduce energy per service unit. This is characterized as "within-technology" efficiency improvement, before accounting for effects of fuel and technology switching such as electrification. The third effect isolates electrification's impact in reducing final energy consumption due to the electric technologies' greater end-use efficiency. The modeling also isolates the corresponding increase in electric demand due to electrification, indicated in dark blue on the left panel of Figure 4-3a and in the darker three colors by sector in the right panel of Figure 4-3a.

Electricity demand in the ***Reference*** scenario increases by around 30% by 2050, with the largest share of this growth in transportation. Without the electrification effect, electricity demand would decline slightly over time, driven by efficiency gains in traditional electric end uses. This is shown on the right panel in the buildings and industry categories labeled "before electrification." Non-electric final energy as a whole declines as a result of these three effects, but the decline is most acute for coal and petroleum. End-use demand for natural gas increases, for reasons summarized later in this chapter in a key finding on natural gas.

In the ***Transformation*** scenario (Figure 4-3b), the high carbon price drives additional energy efficiency improvements and additional electrification, leading to lower total final energy, lower direct use of non-electric fuels, and higher electricity demand. As discussed in Chapter 3, the addition of carbon mitigation incentives primarily drives increased electrification in the buildings and industry sectors, increasing electricity demand more than 50% by 2050. While 50% growth in electric load may appear large, it represents 1.2% annual growth, which is less than half the electric load growth rate realized in the 1990s.

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[33] For example, the Energy Information Administration's Annual Energy Outlook 2018 projects slow final energy growth for the United States across a wide range of future scenarios.

[34] Energy efficiency assumptions are informed by years of extensive laboratory testing and field demonstration projects, combined with observations of advances being driven by customer technologies—see for example, *The Third Wave of Energy Efficiency*, https://www.epri.com/#/pages/product/3002009354/.

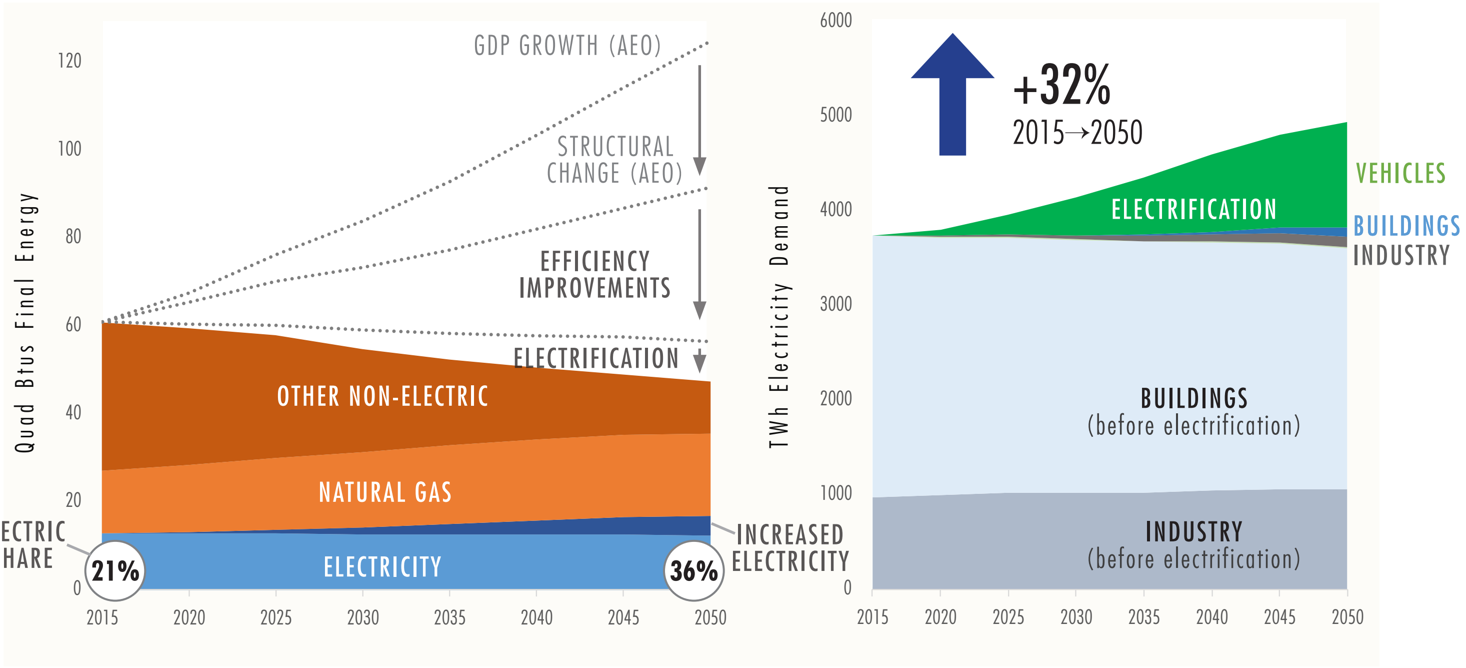

Figure 4-3a. Reference scenario projections for U.S. total final energy by fuel (left) and electricity demand (right). Energy use declines despite economic growth due to structural change, efficiency, and electrification. Electric final energy is shown by sector, distinguished between existing services ("before electrification") and increased service demand through electrification.

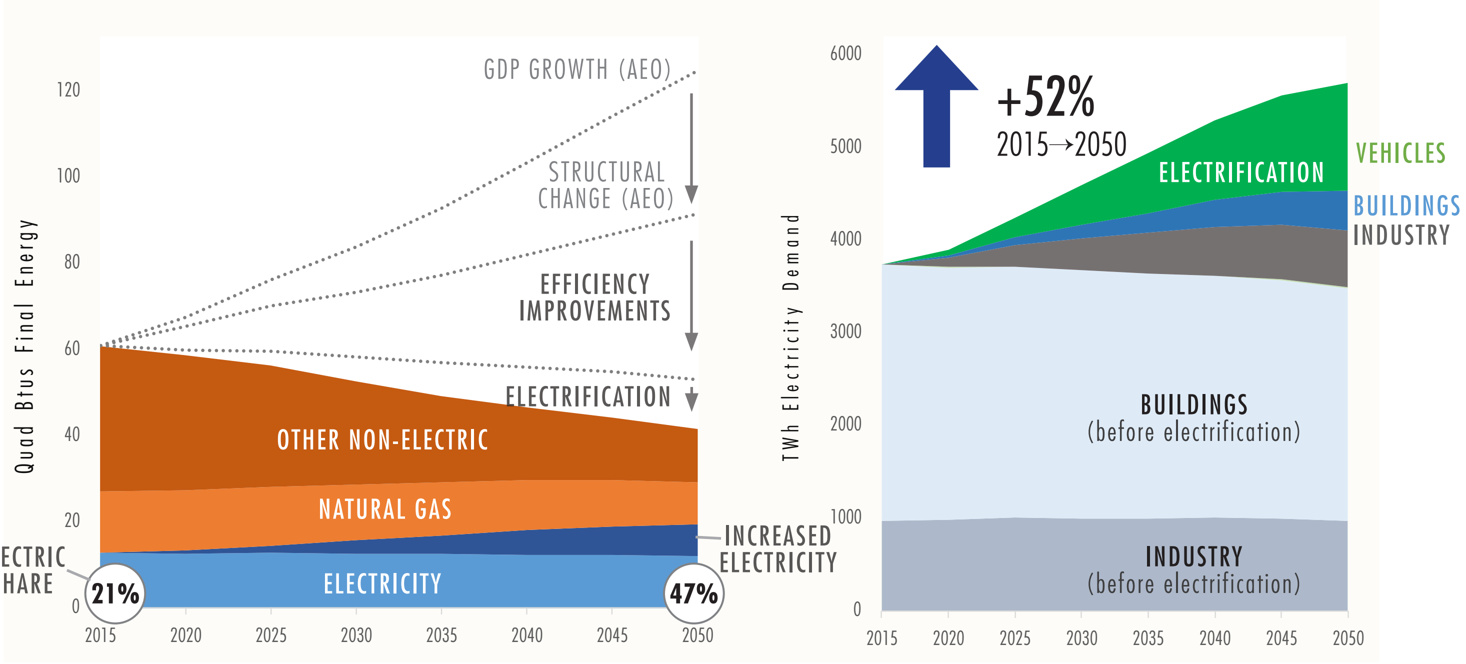

Figure 4-3b. Transformation scenario projections for U.S. total final energy by fuel (left) and electric demand by sector (right).

KEY FINDINGS–NATURAL GAS USE INCREASES

In the United States, natural gas is a low-cost, seemingly abundant fuel. Its importance to the electric sector has grown since the late 1980s and recently surpassed coal as the most-used fuel for power generation. Natural gas use continues to grow in all four EPRI scenarios based on its operational flexibility and an assumed cost of around $4/MMBtu. The continued transition to gas creates both economic and environmental benefits (e.g., lower emissions than petroleum, which it often replaces in industry and lower emissions than coal when used for electric generation). Direct gas use in industry and gas-fired electric generation grows while gas use in building heat remains relatively flat over time. Electric heat pumps with gas backup become attractive technologies in colder regions, utilizing the best features of both and providing additional reliability. In the ***Transformation*** *case (which assumes a significant and growing carbon price), carbon capture and sequestration technology (CCS) enables natural gas to increase its share of electric generation, outweighing declines in the direct end use of natural gas. In sensitivity analyses which assume that natural gas prices rise gradually to about $6/MMBtu by 2050, natural gas use increases in both direct end use and for electric generation.*

As the electric sector's reliance on natural gas grows, it is increasingly important to incorporate gas supply modeling in reliability assessments. Recent disruptions in natural gas supply[34] *highlight the importance of considering broader natural gas supply uncertainty in planning.*

Another area in which gas may compete, and which was not modeled in detail, is gas for combined heat and power. Electric grid modernization is key to unleashing the benefits of these technologies.

The electric sector generation mix supplying these loads varies across time and scenario assumptions, as illustrated in Figure 4-4. The generation differences across the scenarios result primarily from different assumed carbon prices that change the relative economics of generating technologies, different projections of total electricity demand, and changing load shapes as the mix of electric end-uses changes. Despite fundamental uncertainty on the generation side, the same assumptions about cost and performance of generation technologies were used for all four scenarios. For both the *Conservative* and *Reference* scenarios, the share of generation fueled by natural gas increases to meet growing demand. For the *Progressive* and *Transformation* scenarios, the electric generation portfolio becomes less carbon-intensive, including variable renewable energy, nuclear, and CCS generation. The portfolio could shift given different assumptions about technological change, markets, and policies. However, several broad findings are consistent across a range of assumptions:

- For many end uses, shifts to electricity are driven less by the specific electric generation mix than by a growing consumer preference for electric end uses, described earlier.
- National (and regional) generation portfolios are diverse, and although natural gas and renewable generation increase in many scenarios, no single technology dominates.
- Coal use declines in all scenarios, and plant retirements accelerate given carbon pricing under the *Progressive* and *Transformation* scenarios, which entail greater reduction in the emissions intensity of electric generation.

EPRI will continue to test the sensitivity and robustness of these modeling results, but important insights emerge from the current analysis despite uncertainty.

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35. For example, a 2015–2016 Aliso Canyon natural gas storage leak in southern California led to the ongoing closure of the nation's fourth largest natural gas storage facility and the need for electric companies and state regulators to take extraordinary and costly measures to maintain electric system reliability in the Los Angeles basin. Extreme weather can also create disruptions. The Polar Vortex created significant challenges to regional energy systems in January 2014 due to the breakup of the Arctic polar vortex.

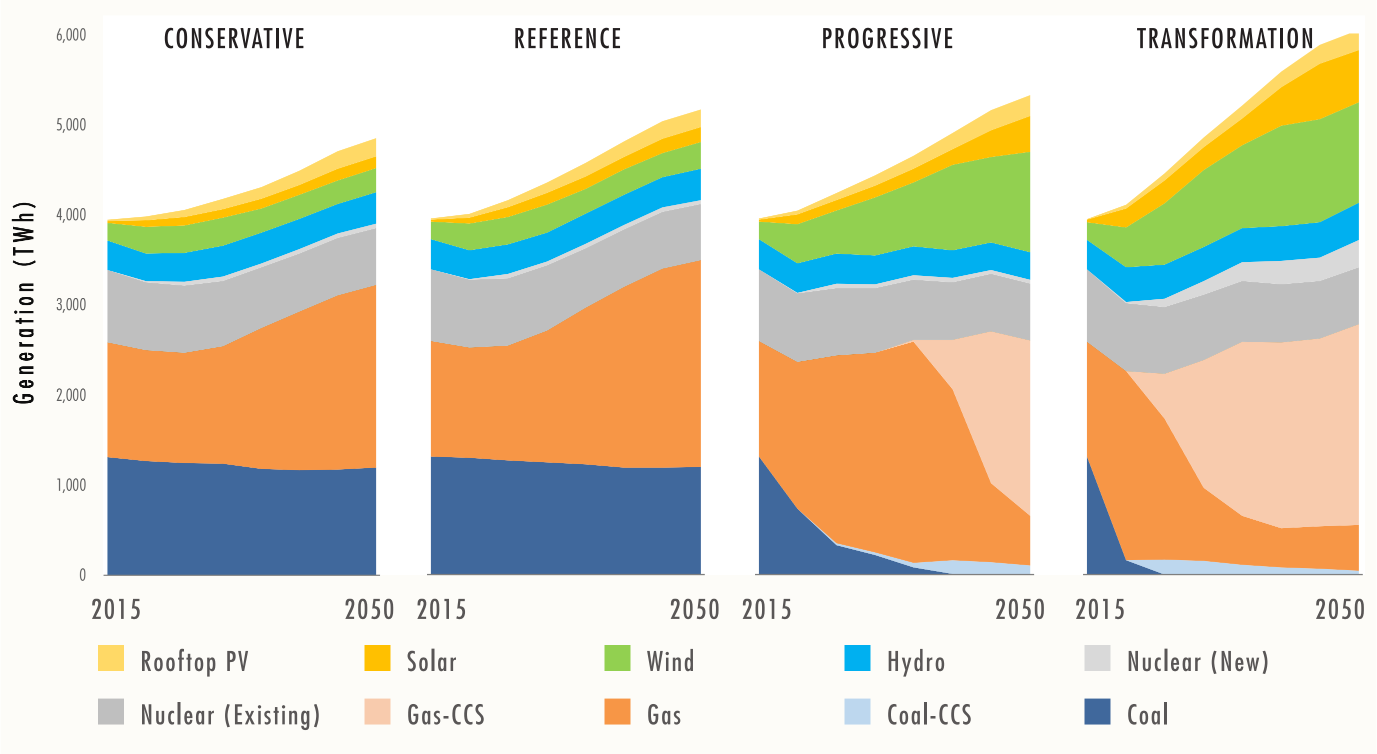

Figure 4-4. Electric sector generation mix over time by technology and scenario.

The assessment's main scenarios are based on the low natural gas price trajectory published in the U.S. Energy Information Administration Annual Energy Outlook (AEO 2017). Given this assumption, demand for natural gas is projected to grow across all scenarios alongside the electrification trend.

While vehicle electrification leads to significant reductions in liquid fuels demand, the scale of electricity substitution for natural gas is lower for buildings and industry. For space heating in colder climates, natural gas continues to serve as both primary and back-up fuel. Continued low natural gas prices drive oil-to-gas switching in industry (these sectoral results for buildings and industry are described in Chapter 3).

Natural gas–fueled power generation's share increases in the ***Reference*** scenario. It increases even more in the ***Transformation*** scenario when equipped with carbon capture and storage (CCS), serving as an important balancing resource for variable renewable generation in this scenario.

With a higher wholesale natural gas price (based on the AEO 2017 reference case—Figure 2-4), the analysis points to greater penetration of electric end-use technologies, but the effect is relatively minor, in part because higher natural gas prices also cause electricity prices to rise somewhat. Electricity's share of final energy by 2050 increases by only one percentage point in the ***Reference*** scenario with a $2/MMBtu increase in the natural gas price.

Figure 4-4 also depicts a growing role for renewable energy, with significant growth in the ***Reference*** scenario and much greater growth assuming imposition on a carbon price in the ***Transformation*** scenario. With higher gas prices, the renewable role is increased in both scenarios. The renewable penetration would also be much higher in the ***Transformation*** scenario if carbon capture and storage were unavailable.

KEY FINDINGS—LOW-CARBON ELECTRIC GENERATION EXPANDS

The carbon intensity of electric generation has fallen in recent years due to lower natural gas prices and increased penetration of solar photovoltaic (utility scale and distributed) and wind generation. Renewable energy continues to grow across all scenarios driven by cost declines and state-level policies. In the carbon price scenarios, the share of wind and solar increases more rapidly as part of a diversified portfolio of low-carbon energy sources. Due to the declining marginal value of intermittent renewable energy, economic penetration is ultimately limited, with nuclear and gas with CCS balancing the mix and providing firm capacity. The assumption that natural gas prices remain below $4/MMBtu across the scenarios implies a larger role for gas with CCS in the carbon price scenarios, although the large-scale availability of this technology remains uncertain. In sensitivity analyses in which natural gas prices are assumed to rise gradually over 35 years to $6/MMBtu, wind, solar, and nuclear all have increased generation shares.[36]

As solar and wind generation capacity increases, the power system must operate more flexibly to accommodate the variable output. Although not explicitly modeled in this study, the addition of flexible loads could emerge as a central strategy to enabling renewable generation growth.

An Integrated View of Energy System Changes

Sankey diagrams provide another depiction of current state and projected changes across the energy system that support the findings above. These show the movement of fuels from extraction through processing, transformation and transport to end use.

Figure 4-5a shows the current energy system. On the supply side, renewable energy use is small; natural gas plays large roles in electricity generation, buildings (primarily for heat), and industry; coal is used primarily for electric generation; and petroleum dominates transport and plays a significant role in industry. Final energy use in buildings, industry, and transport are comparable in size.

Figure 4-5b shows the ***Reference*** scenario projected energy flows in 2050. Natural gas use for electric generation and industry has grown significantly while its use in buildings has remained steady. That growth derives in large part from substitution for petroleum in industry and substitution via electric generation for petroleum in transport. Consequently, petroleum use declines significantly in this scenario. Note that solar, wind, and hydro inputs to electric generation appear small (in part) because they are depicted as lossless generation technologies. Coal, in contrast, loses 60% of its heating value in conversion to electricity. Coal use remains significant in the ***Reference*** scenario, which assumes no climate-focused policy. Buildings, industry, and transport all show significant reductions in energy use (i.e., appear smaller in the diagram) due to efficiency and electrification–results that have been discussed earlier.

Figure 4-5c shows energy flows for the ***Transformation*** scenario in 2050. Solar and wind inputs to electricity generation have increased relative to the ***Reference***. With the assumed carbon price approaching $360/ton of CO_2 in 2050, direct natural gas use in buildings and industry decreases, but natural gas inputs to electricity generation–mostly paired with CCS to control carbon emissions–increases substantially. Coal use drops dramatically in the ***Transformation*** scenario, though this decline would be attenuated if natural gas prices were to rise; in effect, gas with CCS, coal with CCS, and nuclear compete to provide low-carbon, dispatchable generation.

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36. Given this study's focus on energy demand, only a few scenarios were examined for exploring generation. Key factors other than the price of natural gas, the value of carbon, and the availability of CCS that affect the technology mix include: renewable mandates, cost declines and technology change over time, relative costs of capital, the evolution of electricity markets (which affect both the total capacity of renewables and the relative economics of central versus distributed PV), the cost and availability of transmission, the cost and duration of storage, environmental constraints other than CO_2, the impact of renewable variability on the cost of the rest of the system, and flexible load. EPRI research has explored these factors in many other studies. Recent examples include: A 2017 model comparison paper from NREL, EPRI, EIA, EPA and DOE, *Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective*, https://www.nrel.gov/docs/fy18osti/70528.pdf.

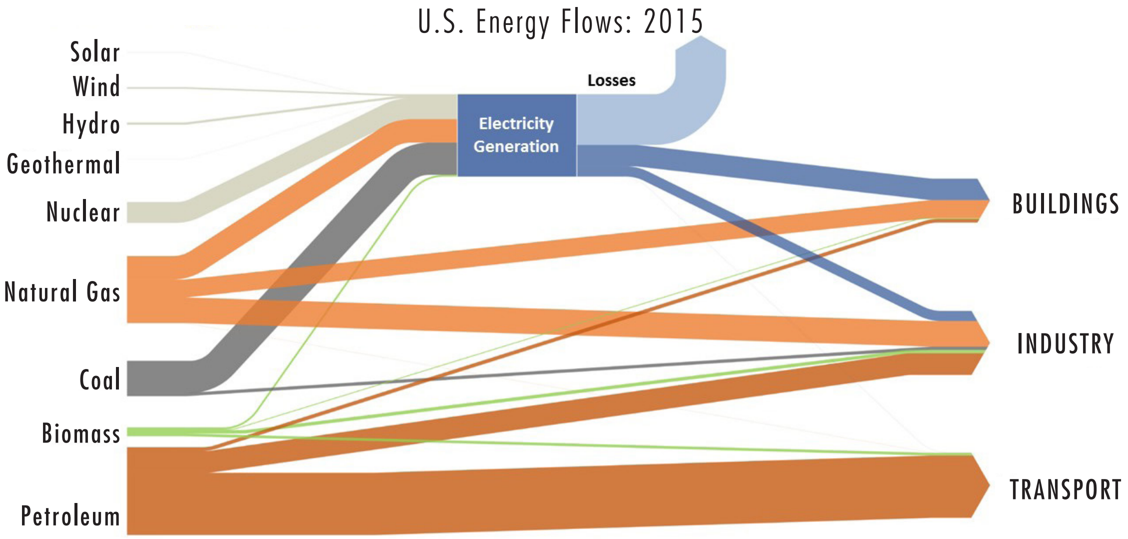

Figure 4-5a. Sankey view of 2015 energy profile.

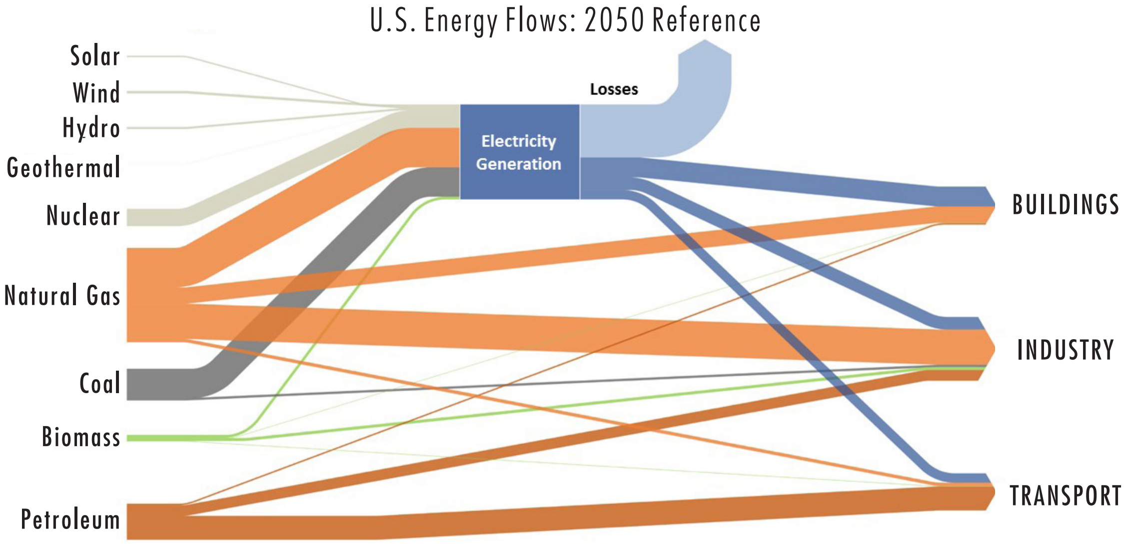

Figure 4-5b. Sankey view of 2050 Reference scenario projection.

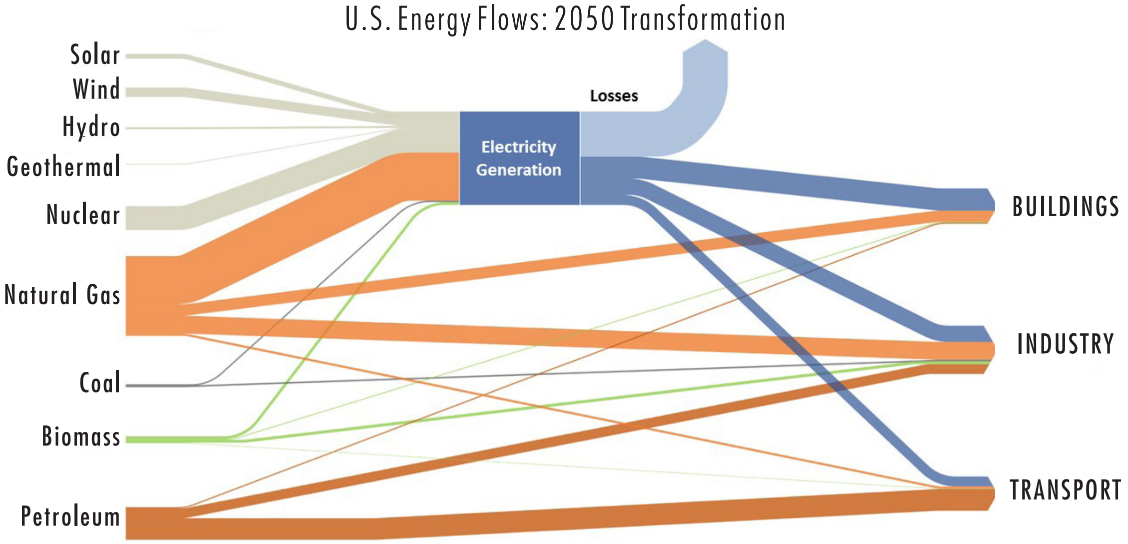

Figure 4-5c. Sankey view of 2050 Transformation scenario projection.

KEY FINDINGS—EMISSIONS DECREASE

In nearly every cost-effective application, electrification also lowers system-wide carbon emissions. Even absent a carbon policy, projected CO_2 emissions fall 20% by 2050 in the Reference scenario, driven by efficiency gains and efficient electrification. Although not modeled in this analysis, other EPRI research suggests that electrification can improve local or regional air quality by reducing criteria pollutants. Policies that provide an active signal to cut emissions (the Progressive and Transformation scenarios) lead to even greater environmental improvements—notably through a more rapid shift to electricity. For the Transformation scenario, electricity's projected share of total energy reaches nearly 50% by 2050, with emissions falling to nearly 70% below 2015 levels. Figure ES-2 summarizes energy consumption, CO_2 emission, and load projections for 2050 across the four scenarios.

Shifts to electricity and natural gas as end-use fuels, combined with shifts to natural gas and low-carbon technologies in electric generation, result in declining carbon emissions even absent any new carbon policy (Figure 4-6). In nearly every application for which electrification is economically efficient, the result is lower system-wide carbon emissions. With policy incentives for emissions reductions the value and potential scope for efficient electrification increases. In the ***Progressive*** and ***Transformation*** scenarios, the electric generation mix becomes less carbon-intensive, as discussed above. More widespread adoption of electric end-use technologies, especially in the buildings and industrial sectors, becomes cost-effective for reducing carbon emissions relative to direct fossil consumption.

Although not examined in this analysis, improvements in air quality through reduction in criteria pollutants can be a more immediate driver for electrification in some regions, as can water benefits, health and safety, and other environmental factors.

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37. *The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources.* https://www.epri.com/#/pages/product/000000003002002733/.

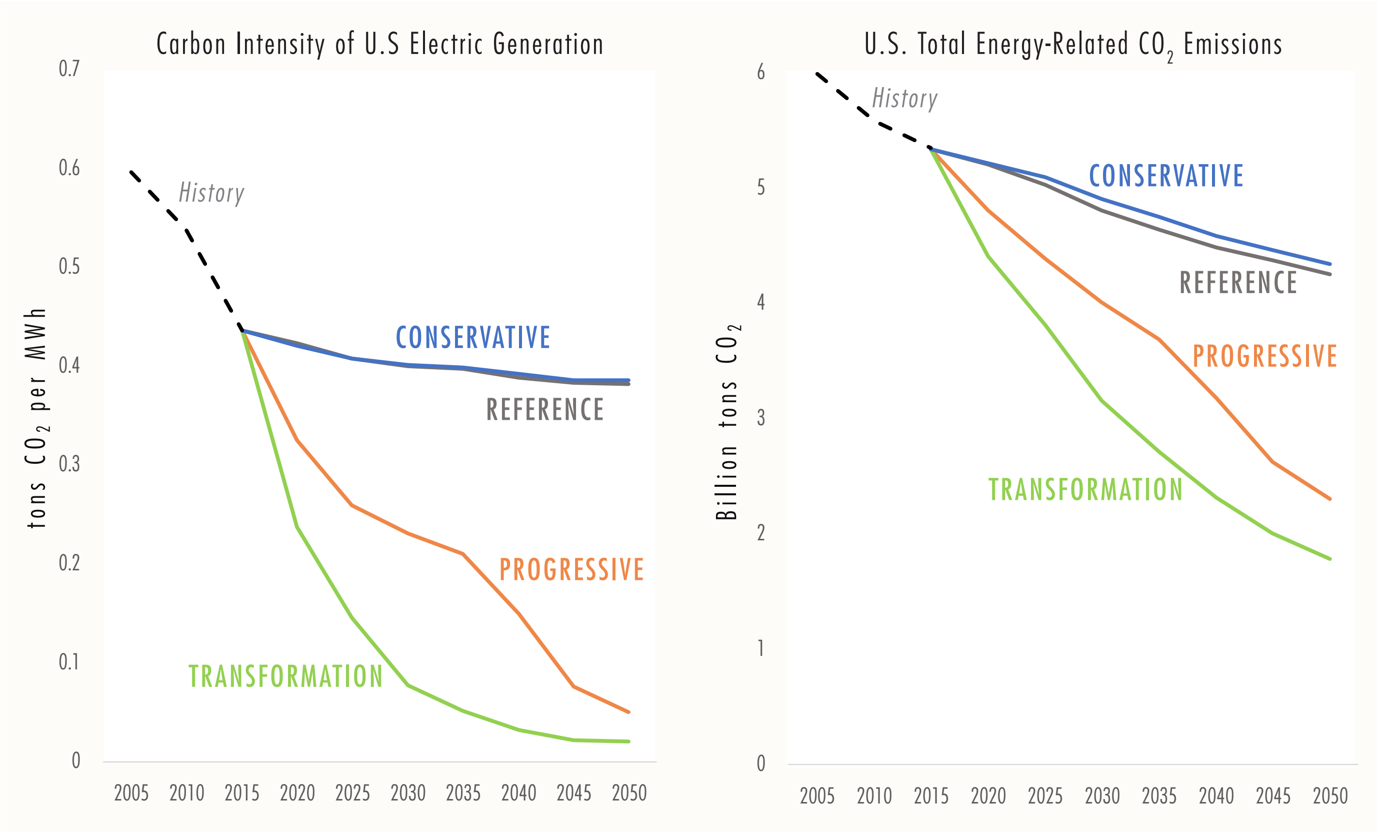

Figure 4-6. U.S. carbon intensity of electric generation (left) and total energy-related CO_2 emissions (right) across all four scenarios. *Conservative scenario assumes slower improvement in electrification technology. Progressive and Transformation scenarios assume an economy-wide carbon price starting at $15/tCO2 and $50/tCO2 respectively in 2020.*

KEY FINDINGS—PRESSURES INCREASE TO MODERNIZE GRID INFRASTRUCTURE, OPERATIONS, AND PLANNING

As the end-use mix includes more vehicle charging and heat applications, seasonal low temperatures will drive heating demand, while reducing the efficiency of electric vehicles—resulting in a shift in overall loads toward the winter months. While electricity demand in most U.S. regions peaks during the summer, peak loads could shift to winter by 2050 across the USNEA scenarios, assuming no efforts to actively manage loads. At the same time, these new electric loads provide significant opportunities for more flexible and responsive demand response, as well as storage. Realizing such benefits is contingent on investment in a flexible, resilient, and integrated grid[37] *and clear electricity market signals. Such demand-side changes coupled with more diverse, dynamic electric supply, create an array of challenges and opportunities for system planners and operators.*[38]

Electrification affects electric sector resource planning with respect both to overall load growth and changing patterns of electricity demand. In this analysis hourly load shapes are built up from individual end uses, revealing changes to both diurnal and seasonal system shapes as the end-use mix shifts to include more vehicle charging, heat, and other electric applications (Figure 4-7b). Low temperatures drive heating demand, and reduce electric vehicle efficiency, which by 2050 combine to produce strong winter peaks in most regions in the scenarios (today for most regions of the United States loads peak in the summer). Meanwhile, efficiency improvements in cooling technology offset growth in service demand, limiting increases to the traditional summer peak over time. Although not explicitly modeled in this analysis, other research highlights that with greater electrification, the diurnal load shape may be more flexible, depending on how charging behavior responds to rate-based incentives and the potential for advanced thermal storage strategies to shift heating and cooling demand.

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[37] *The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources.* https://www.epri.com/#/pages/product/000000003002002733/.

[38] See Integrated Energy Network-Planning paper, EPRI 3002010821 (forthcoming 2018).

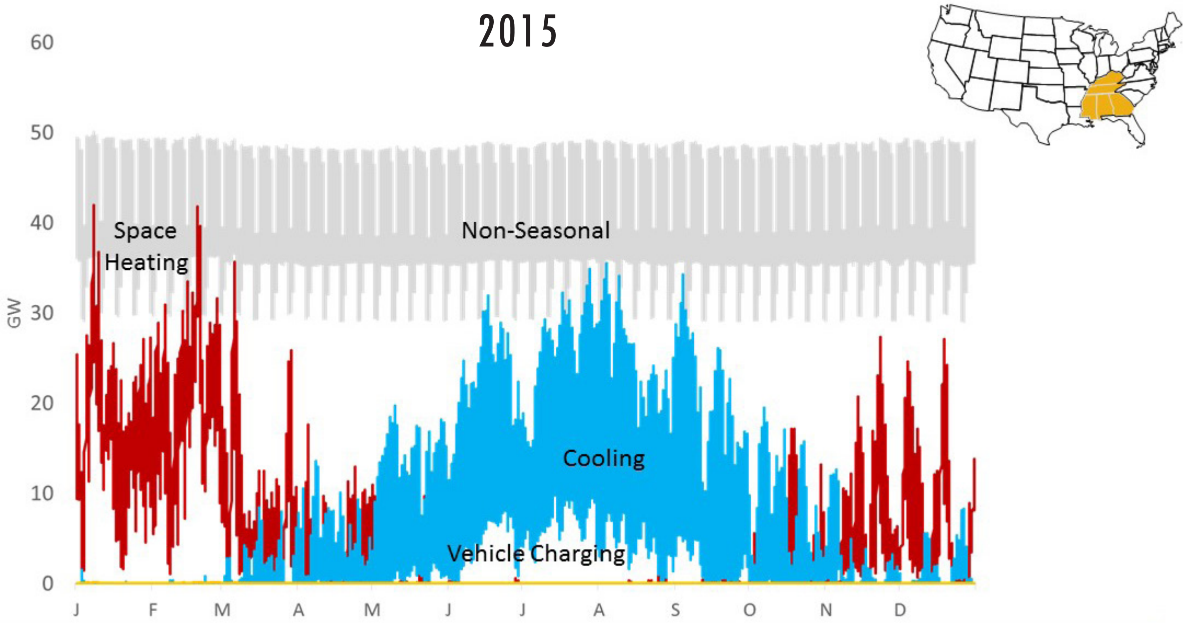

Figure 4-7a. Hourly load profile by end-use category for Southeast model region in 2015.

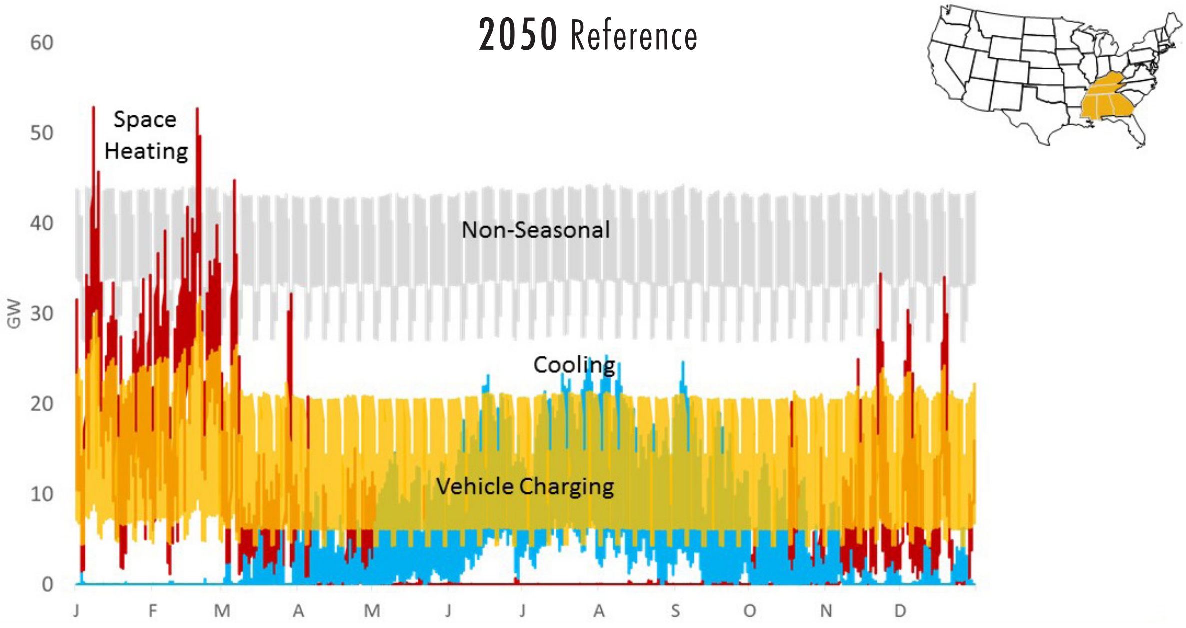

Figure 4-7b. Hourly load profile by end-use category for Southeast model region in 2050 in Reference scenario projection.

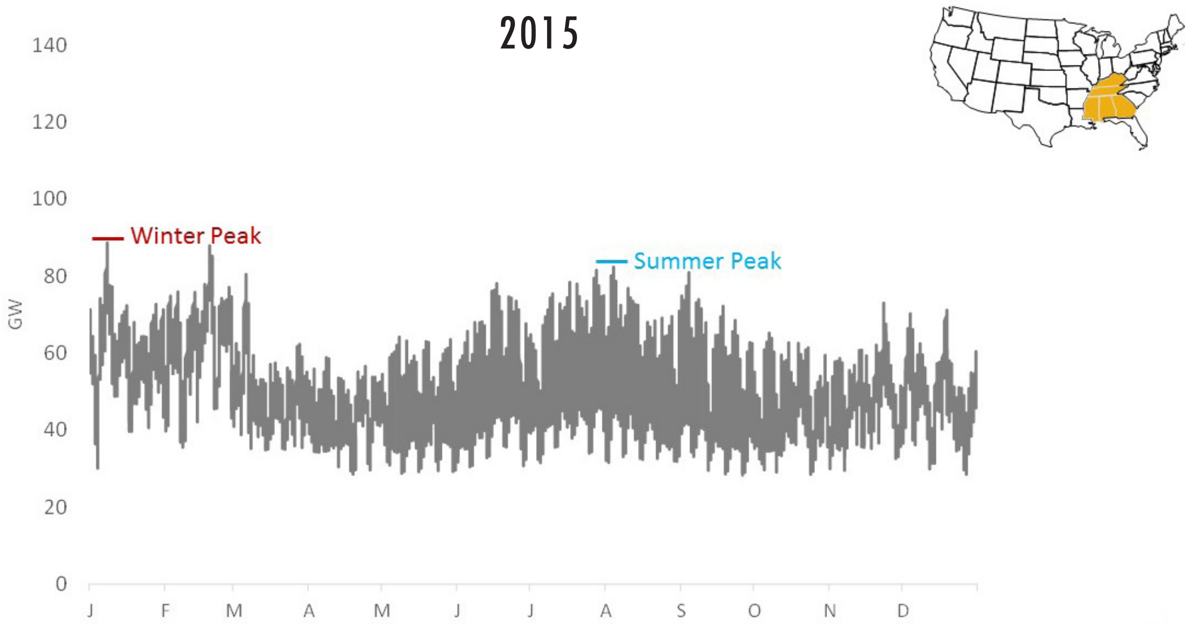

Figure 4-7c. Aggregate hourly load profile for Southeast model region in 2015.

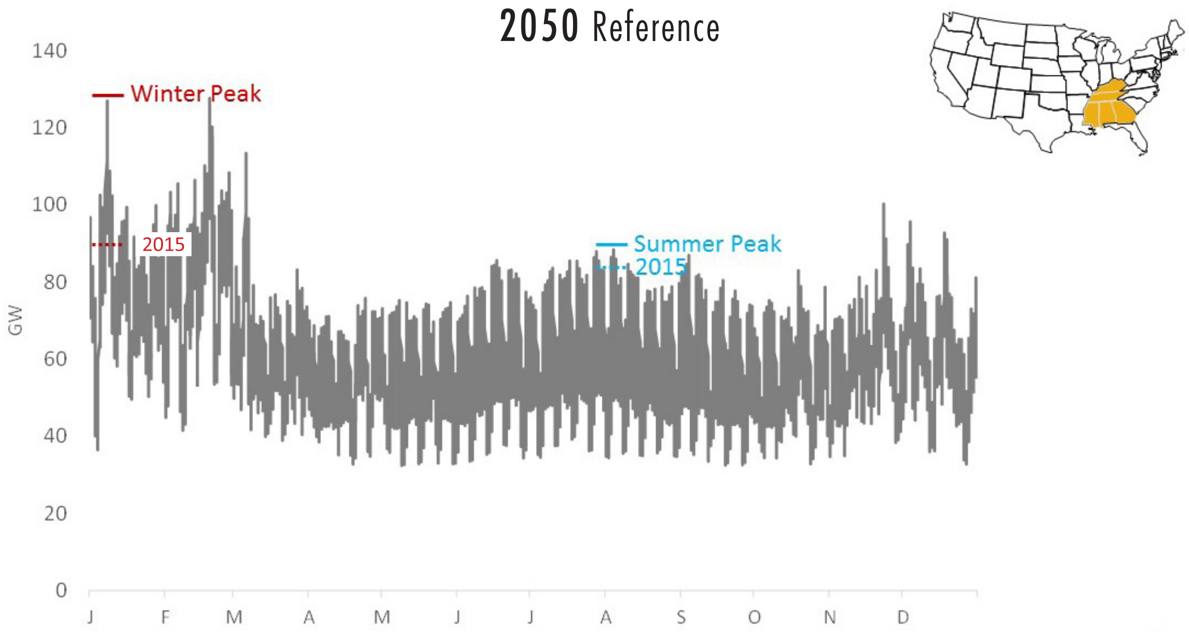

Figure 4-7d. Aggregate hourly load profile for Southeast model region in 2050 in Reference scenario projection.

With respect to any model projections, uncertainty is a given. The USNEA scenarios examined variations in environmental policy and natural gas price and explored some sensitivities on key technology costs. Cheaper, more efficient technology options reduce costs and spur growth in general and provide even more value when they provide needed services to the system.

While EPRI's assessment covers the technological and economic potential for electrification of existing end uses, several more transformative shifts are emerging that could increase electric demand, improve resource efficiency, and offer new or enhanced services:

- Indoor agriculture is emerging to bring food production close to markets, reduce impacts on land and water resources, and reduce transportation energy use and costs. Advanced processes for producing protein may provide new, lower-impact options for producing meat and meat substitutes.
- Additive manufacturing, to bypass traditional manufacturing technologies and supply chains, offering new possibilities for production and delivery.
- Electro-synthesis of chemicals, replacing processes that today are entirely fossil-fueled.
- Automation and artificial intelligence, in particular autonomous vehicles, which could transform the mobility-as-service model and revolutionize long-haul freight.

Successful development and deployment of autonomous vehicles could fundamentally change the economics of transport, accelerating a shift to electricity. A major economic advantage of driverless vehicles is the potential for much higher utilization rates and synergy with a low-operating cost electric battery platform. If mobility-as-service can be offered at a sufficiently low price (which could be achieved through autonomous technology), an alternative business model emerges for an alternative to vehicle ownership, particularly for low-mileage drivers. This could further increase electricity's share of vehicle miles. Charging patterns of a centrally managed fleet could be much more flexible and easier to integrate than private vehicle charging. Such a disruptive shift could have strong feedbacks on many aspects of transport service demand, from access to currently underserved populations to changing spatial patterns of cities.

Considered together, these point to diverse and far-reaching opportunities for electrification research to define promising technological applications and to account for benefits that may accrue to energy producers, transporters, and consumers.

KEY FINDINGS–TECHNOLOGY INNOVATION LOWERS COSTS AND CREATES OPPORTUNITIES

Realizing electrification's benefits depends on continued innovation in electrification technologies that reduce costs and improve performance. The value is significant in all scenarios, but is greatest in the ***Transformation*** *scenario, in which policy establishes a high value on lower emissions. Yet, economics alone and broader customer awareness will not be sufficient to realize the full potential for society. Industry stakeholders will need to build upon lessons learned from past successes, such as utility-administered energy efficiency programs. In addition, effective rate designs coupled with policy and regulatory frameworks can be structured to support investment in electrification end-use technologies and enabling infrastructure, including a more resilient, integrated electric grid.*

5. ACTIONS TO REALIZE THE FULL BENEFITS OF EFFICIENT ELECTRIFICATION

The U.S. National Electrification Assessment brings into focus the potential for efficient electrification to transform the energy system. Yet it points to many actions that appear necessary to realize the full benefits. All require research, development, and demonstration to develop and test technologies and to inform policy, regulation, and market choices (which will be made at national, regional, state, and local levels) by examining how alternative designs may impact the grid and the energy system.

- *Accelerate technology research, development, and demonstration*

  Technology research, development, and demonstration in all aspects of the electric system, from generation to delivery to end-use, can help provide better and cheaper energy solutions.

  Cleaner electricity production. Cleaner, more efficient power generation is essential to realize the full environmental benefits of efficient electrification. Electric generation has reduced its environmental footprint significantly over the past decade. Future gains depend on continued improvement of renewable energy, natural gas, coal, and nuclear technologies; increased flexibility in dispatch and improvements in storage; expansion of sustainable biofuels; and development and demonstration of CCS. Actions that can help enable cleaner electric generation include investments in a broad range of low-carbon technologies.

Develop and Demonstrate Cleaner Electric Generation Technologies

- *Create advanced renewable technologies; develop a better understanding of renewable energy integration challenges; and inform policy, regulatory, and business models.* Next-generation renewable technologies are essential to reduce costs further and increase capabilities to operate more efficiently as part of the overall system. At the same time, policy, business model, and technical approaches must progress in concert to realize the full benefits of variable renewable production. An integrated portfolio of technologies should be explored for dealing efficiently with daily and seasonal variability. This includes improved use of forecasting, expanded long-distance transmission, diverse storage options, demand response, and hydrogen. Market, regulatory, and communication and controls advances are required to enable and sustain the system's efficient, reliable operation as variable resources are added. Environmental research is needed to anticipate and address emerging environmental issues associated with these technologies.
- *Demonstrate advanced low-emission fossil technologies and the policies, regulations, and standards needed to support them.* Research is essential on advanced power cycles and on carbon capture, storage, and utilization. Support for demonstrations is needed for capture technologies at scale, basic research is needed to examine use of CO_2 captured, and regulations are needed to deal with underground storage.
- *Support development of new nuclear designs and the policies, regulation, and standards needed to support existing and new nuclear.* Advanced reactor designs and government policies are needed that support development of new plants and continued operation of existing plants.
- *Explore bioenergy technology options, carbon accounting, feedstocks, and policies, particularly bioenergy with CCUS.* Bioenergy with CCUS is assumed to be deployed widely in most scenarios that achieve the long-term goals of deep carbon reduction (e.g., the goals of the Paris Climate Agreement). Research must address many questions regarding the production and control technologies and sustainable, large-scale, low- or no-net-emission fuel supplies.
- *Explore the role of hydrogen as a clean carrier of energy and the economic and policy impediments to its development.* Research must focus on producing hydrogen cleanly, on business models for developing a hydrogen infrastructure, and on safety.
- *Explore flexible operation opportunities for all generation technologies.* R&D addressing aspects or features of the technologies above that support variable power generation through fast ramping, advanced inverters, long-term storage, or other technology is needed.

Grid modernization. Grid investment must enable the dynamic matching of variable generation with demand, while supporting new models for customer choice and control. Investments are needed also to maintain reliability and enhance resiliency. Grid capacity planning and operation will need to address the integration of electric transportation networks with the grid through smart charging, fast charging, and storage utilization.

A first step is to create the Integrated Grid to enhance resilience, reliability, efficiency, and customer services through the effective integration of central and distributed electric resources.

Create the Integrated Grid

- *Develop interconnection rules and communications technology and standards.* Rules and tools are needed to support real-time data transfer and to address privacy. This requires technology development and standards development along with regulatory and policy support.
- *Assess and deploy advanced distribution and reliability technologies,* including smart inverters, distribution management systems, sensors, distributed energy storage, and demand response and the communication and information technology infrastructure to tie them together. Regulatory support is needed for testing and demonstrating promising technologies.
- *Create strategies for integrating distributed energy resources with grid planning and operation* for efficient and effective system planning and operations. Efficient investment and operation of the electric grid require broad, specific coordination across customer, distribution, transmission, and generation planning functions. This requires new tools and processes for companies as well as regulatory support.
- *Inform policy and regulation development to enable flexible yet reliable operation of the electric system for effective DER integration,* reflecting the costs and benefits of the various components and systems. Much remains to be done for providing detailed assessments and for determining costs and benefits of electric system components. Fundamental challenges value depends on location and on what else is connected; with the result that value will change over time.
- *Strengthen and expand the transmission system to maintain reliability and enable more flexible operation.* Inspection, assessment, monitoring, and investment are needed to ensure transmission system reliability, given rapid changes in electric generation technologies and locations. Transmission system expansion will enable integration of variable generation and loads and will be essential to support electrification. New "lower–impact" substation and line designs are among the technologies needed to increase public acceptance, reduce costs, and maintain reliability.

As the Integrated Grid develops, it becomes instrumental in developing and applying comparable smart technologies for natural gas, water, and other systems. While these systems' needs differ, they have much in common with respect to sensors/meters/switches, communication, data analysis, and cyber security architectures. They can be made interoperable through development of an architecture, operational principles, and procedures that include data format and communications systems.

Improve Connections Across the Energy System

- *Identify ways to integrate systems as they are automated for production, delivery, and use of electricity, natural gas, and water.* Common elements among devices, architectures, and software may support and drive common interests, approaches, and solutions.
- *Assess key interfaces between gas and electric systems and markets; explore market integration.* Include comprehensive consideration of environmental challenges and opportunities, integrated modeling of operations and planning, and market integration to achieve efficiency.
- *Assess key interfaces between energy and water* to enable efficient water use to support more flexible operation of the electric system and to improve environmental performance.
- *Develop diverse capabilities for managing, assessing, and analyzing "big data"* to meet the future energy system's dynamic, real-time requirements.

Continued, rapid advances in electric end uses. Falling battery costs, digitalization, advances in materials, and increasing production scale can improve the efficiency and performance of a range of electric technologies, from automobiles to industrial equipment. Transformative shifts on the horizon include mobility-as-service models and autonomous vehicles, indoor agriculture, additive manufacturing, and electro-synthesis of chemicals.

Many advances in electric end-use technologies will be direct or spillover effects from advances in consumer electronics as a "third wave of energy efficiency" spurs wide ranging advances.[39] Specific actions that EPRI is taking to help ride this wave are highlighted below.

Improve Electric End Uses

- *Advance key end-use technologies and integrating technologies.* Focus research developing and field testing advanced electric technologies to move digital and materials progress into commercial products. Advances in heat pumps and heat pump water heaters are initial steps in developing new, innovative electric technologies. EPRI provides a platform where vendors can field test new prototype equipment to gain operational experience, improve design, and gain potential customers.
- *Create networks and Centers of Excellence to catalyze technology innovation and communication.* A key element of EPRI's Efficient Electrification Initiative is to catalyze and connect centers for excellence at universities, national laboratories, and elsewhere to explore and provide information on advanced electric technologies. The aim is to leverage the significant research efforts underway and expertise spread around the world to greater benefit.

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[39] See for example, *The Third Wave of Energy Efficiency*. https://www.epri.com/#/pages/product/3002009354/.

- *Develop new analytical tools*

More in-depth studies of opportunities and challenges of efficient electrification. The USNEA provides a starting point for considering and examining efficient electrification, offering insights and a framework for additional analyses. For the United States and other countries, detailed regional studies are needed to understand more realistically the costs, the benefits, and the barriers that will drive customer choices in varied circumstances.

Develop Tools to Increase Understanding of Broad-scale Opportunities and Challenges for Efficient Electrification

- *Conduct state-level assessments to gain a clearer understanding of efficient electrification opportunities and challenges.* State-level assessments provide fundamentally new insights given differences in urbanization, transportation infrastructure, electric infrastructure, air quality, policy objectives (e.g., reducing greenhouse gases or improving air quality), industrial opportunities, and so on. More limited geographic scope and local perspectives will be used to drive the modeling enhancements needed to support clear assessment of technology choices.
- *Conduct non-U.S. assessments to broaden understanding and perspective.* Although U.S. states are quite diverse, much can be learned from exploring efficient electrification outside the United States, for example in rapidly developing economies, in countries planning large carbon reductions, and in areas where the current distribution grid may limit the amount of electricity use in homes.
- *Advance modeling of end-use flexibility.* Key opportunities of efficient electrification are also important opportunities for adding flexibility to the grid. Controlling the timing of EV charging, potentially using EV batteries as storage, and flexible operation of heat pump water heaters and heat pumps are opportunities that need to be assessed, and if important, included in models on an equal footing with other generation, storage, and DER technologies.

New cost-benefit frameworks for assessing individual electrification projects. New methods for comparing options in energy services are essential to support informed regulation and to implement programs that address barriers to customer adoption of technologies. Improved understanding of diverse customers' perspectives is essential in building more useful models.

Develop New Frameworks to Understand Application-specific Costs and Benefits

- *Develop robust methods for assessing the costs and benefits of efficient electrification.* New methods are essential to inform regulators and other stakeholders as potential programs are considered to overcome non-economic barriers to adoption of electric technologies, paralleling their efforts to promote energy efficiency, which is discussed further below.

- *Expand focus on reliability and resilience*

  Consideration of reliability and resilience should combine society's increased dependence on electricity, the increasing role of variable renewables in supplying electricity, and advances in digital technology that potentially enable greater system optimization.

  With the spread of electricity to transportation, heating, and other end uses, expectations for reliability will grow. Important social considerations such as security and privacy will be integral to progress and in demonstrating the value of broader electrification to diverse social groups and interests. Hence, public acceptance depends on effective, concerted attention to cyber security and privacy controls in moving to a more integrated, digitally controlled energy system.

  New metrics for reliability. As the electric system relies increasingly on variable renewables and just-in-time delivery of natural gas, it is important to review concepts or reliability, which historically focused solely on the electric system and on resources adequate to satisfy highest demand in the year. Looking forward, system reliability may be stressed in multiple hours in differing ways, and system flexibility, natural gas delivery risk, and other factors may be integral to assess and maintain it.

  Rethink electric system resiliency. The U.S. National Electrification Assessment scenarios depict electricity's expanding role in the energy system, which heightens requirements for resiliency with respect to both natural forces (e.g., extreme weather, seismic event, geomagnetic disturbance) and man-made hazards (e.g., high altitude electromagnetic pulse [EMP], intentional electromagnetic interference [IEMI], cyber terrorism, or coordinated physical assault). As electric systems "go digital" from generation through billions of connected devices, the points of entry for cyber attack and the assets at risk increase exponentially. That same digital capability can be harnessed to locate, isolate, and recover from both natural disruptions and attacks.

  A central question is how much society is willing to pay for increased resiliency. Addressing this question requires understanding the implications of a sustained outage (or equivalently, the value of avoiding or reducing outage severity) and probabilistic risk management approach options.[40] Key aspects of new thinking in resiliency include shared resources, consideration of multiple value streams besides resiliency, probability risk assessment, adequacy of value of lost load (VoLL), and standard/metric-based criteria.

Develop New Approaches to Assess Reliability and Resiliency

- *Focus on security, reliability, resiliency, and privacy.* The U.S. electric system has a long history of reliable performance, yet demands for increased reliability grow each year. Where an electricity outage used to cause concern about "what's in the refrigerator?," today an outage can instantly halt communication, commerce, cooling, entertainment, traffic control, limit health care, and more. With recent extreme events and consequent prolonged electric outages, for example, Hurricane Maria in Puerto Rico, an additional concern has focused on system resiliency—effectively, the ability of the system to bounce back from a high-impact, low-probability event.

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[40] See for example, *Risk Management in Critical Infrastructure Protection: An Introduction for State Utility Regulators*, https://www.naruc.org/bulletin/the-bulletin-011117/naruc-paper-webinar-risk-management-for-critical-infrastructure-protection/.

- *Inform policy, regulatory, and electricity market designs*

  Policy, regulatory, and market advances are also essential to realize the promise of efficient electrification. Here, research can play a key role assessing the effect of alternative designs on the grid and energy system to inform choices that will be made at national, regional, state, and local levels.

Informing Choices

- *Coordinated, economy-wide policies.* The dramatic sectoral shifts projected in all four scenarios highlight the value of taking a broad view of energy policy, rather than addressing issues one sector at a time. New and modified policies in several sectors can more readily enable these shifts where they meet societal objectives. For example, for environmental policy, the national assessment modeling assumes a consistent carbon signal applied to all sectors of the economy. Yet, at present, no country is taking this approach, choosing various policy approaches for different sectors. Policies focused on one sector can limit the interactions among various sectors to achieve societal goals. For example, efficient electrification can be a tool for reducing economy-wide emissions though it could lead to a small increase in electric sector emissions.
- *Updating energy efficiency codes.* A review of energy efficiency measurement and cost tests (e.g., for appliances, heating, and transportation) is needed to remove fuel bias and frame regulations that enable efficient electrification and encourage traditional energy efficiency.
- *Facilitating market transformation.* Targeted programs—similar to efforts with energy efficiency—may be needed to address barriers to efficient electrification where it makes sense economically and among public priorities.
- *Electricity market designs to send the right signals to both supply- and demand-side.* With new electric supply and demand technologies projected to emerge. It becomes increasingly important to value energy, capacity, flexibility, locational value, storage, and other attributes. EPRI's research on advanced energy communities with zero net energy and all-electric homes clearly shows the need for valuing both energy and grid connectivity.

Facilitating Market Transformation: Encouraging Adoption of Efficient Electric Motors

Utility programs for efficient electric motors illustrate challenges of adopting new technologies and subsequent success.

Early utility motors programs featured rebates to commercial and industrial customers, similar to those offered for other energy-efficient equipment such as light bulbs, appliances, and air conditioners. But such incentives did not drive significant market penetration for motors. Evaluations pointed to a lack of availability from motor suppliers. Because motor purchases typically are prompted by the failure of existing motors, immediate product availability was paramount.

In response, utilities targeted incentives to companies that sell motors directly to end-use customers. They promoted premium efficiency motors to vendors and disbursed incentives on sales. Vendor contests promoted program participation and encouraged competition among suppliers. One goal was to boost inventories and improve availability. Utility programs educated suppliers on the advantages of premium efficiency motors, equipping them to educate customers and promote sales. While well-conceived, these incentive programs yielded only marginal market penetration.

Further analysis revealed insufficient inventory up the supply chain. Utilities moved their motor programs up the supply chain. The market power of distributors, coupled with their concentration (i.e., far fewer distributors of motors compared to vendors) made for more manageable and effective programs, which included emphasis on information campaigns coupled with incentives. In California, the move to a distributor-focused program in 1999 resulted in more sales of premium efficiency motors than the previous four years combined.[41]

The upstream motor efficiency programs led to adequate motor inventories and greater customer awareness, which continued to spur sales and to deliver energy savings to utility customers.

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[41] Xenergy. 1999. Nonresidential HVAC and Motors Turnover Programs: Distributor Incentive Program 1999 Milestone Study. San Francisco, California: Pacific Gas and Electric Company.

6. CONCLUSION AND NEXT STEPS

EPRI's U.S. National Electrification Assessment brings into focus the potential for efficient electrification to create value for customers and society, looking across the end-use sectors. Its analyses point to actions needed to define these benefits more precisely and to establish an effective transition.

The analyses suggest that the economic potential for electrification is compelling in many applications and illustrate the importance of adopting an economy-wide perspective of energy, yet realizing this potential requires removing policy and regulatory barriers that impact choice or limit supporting infrastructure.

Load dynamics will change and shift in response to greater electrification, and new electric loads will provide opportunities for more flexible and responsive demand response, as well as storage. Realizing such benefits is contingent on investment in a flexible, resilient, and integrated grid and the development of clear market signals. Demand-side and supply-side changes will present system planners and operators with many new opportunities and challenges.

Industry stakeholders will need to build upon lessons learned from past successes, such as utility-administered energy efficiency programs. Effective rate designs coupled with policy and regulatory frameworks can be structured to support investment in electrification end-use technologies, where consistent with societal choices.

Although not modeled in this analysis, improvements in local or regional air quality through reduction in criteria pollutants can be even more significant in driving a transformation. Improved assessments of these benefits can inform more effective policy choices.

Natural gas recently surpassed coal as the most-used fuel for power generation, and its use continues to grow in all four of the analysis scenarios, which assumed continued low prices. Understanding the reliability impacts of increased reliance on gas and the opportunities its operational flexibility provides are important in the near-term, and the development of CCS technologies can be important where policies drive sharp reductions in CO_2 emissions.

EPRI is moving forward on many fronts to address these and other issues related to efficient electrification. The Institute's near-term actions include:

- Initiate detailed, state-level assessments to examine the costs, benefits, drivers, barriers, and challenges to efficient electrification, integrating local knowledge and circumstances, and pursue similar international collaborations. These studies will examine a broader array of drivers, including local air quality.
- Develop a benefit-cost framework in 2018 for assessing individual projects to support investment and inform regulatory decision making.
- Establish electric technology centers of excellence at universities and other institutions to create, demonstrate, and field test a range of emerging electric technologies.
- Expand research in resiliency and cyber security to address emerging challenges for the electric sector and for society.
- Facilitate awareness across all industry stakeholders and customers through active outreach. Initiate an annual international conference for diverse groups that will drive the electric future—generators small and large, grid operators, end-use vendors, universities, research labs, regulators, policymakers, city governments, businesses, smart communities, and individual customers—to provide the resources they need to understand and realize the benefits of a more electrified world.

In addition, EPRI's Research and Development Portfolio includes many ongoing programs that in their overall scope are directly addressing electrification or aspects of the electricity sector that are directly connected.

Some of the programs focus directly on electric end uses and customer choice:

Electric Transportation

- Research and development on EV and infrastructure technologies
- Analyze economic and environmental impacts of electric transportation
- Public-interest support of electric transportation and awareness

Supplemental research to

- Develop utility-specific PEV adoption models that identify utility options guiding PEV adoption in the service territory
- Consumer behavior modeling approaches to quantify consumer decision making
- PEV adoption forecasting models tailored for individual utilities

End-Use Energy and Demand Response

- Assess, test, demonstrate, and deploy technologies
- Influence progress of codes and standards
- Develop analytical frameworks for utility application
- Accelerate availability of technologies and methods
- Mitigate risk and uncertainty of pilot programs
- Provide tools and techniques to integrate end-use energy and demand with planning

Indoor Agriculture

- Market survey and study related to the trends, concepts, economic impacts, market forces, utility potential, job creation, production efficiency gains, crop yield, and environmental impacts.
- Identify stakeholders and analyze existing research relevant to future work such as collaborative studies, laboratory evaluations, and field demonstrations.

Next Generation Heat Pump

- Define use cases for testing and a test protocol/metrics for evaluation.
- Field test units from various manufacturers to verify capacity, efficiency, maintenance needs, flexibility, CO_2 reduction, and more.
- Work with manufacturers to finalize designs conforming to an NGHP specification.
- Distribution operations and planning.
- Advancement of distribution planning practices, methods, and tools.
- Identification and application of new protection techniques for improved grid resiliency.
- Advancement and incorporation of new approaches for modernizing grid operations.

Electrification for Customer Productivity

- Provide an analytical framework for quantifying electrification potential in a region or service territory.
- Provide a framework for assessing electrification's net value to business customers, the utility, and society.
- Web-based knowledge base and decision support tool utilities to screen electrification applications.
- Training modules on technologies for sales teams.

Other programs focus primarily on integrating these technologies, making the grid work efficiently, and informing policy, regulatory, market design, and customer choices:

Energy, Environmental, and Climate Policy Analysis

- Identify important drivers for electrification, including technological change, carbon and other environmental policies, and new business models.
- Understand interactions of drivers and policy designs that can take advantage of electrification opportunities.
- Examine impacts of electrification and other end-use shifts on electric system operation, and improvements, such as changing load shapes, demand response, and increased demand growth over time.

Distribution Operations and Planning

- Advancement of distribution planning practices, methods, and tools
- Identification and application of new protection techniques for improved grid resiliency
- Advancement and incorporation of new approaches for modernizing grid operations

Still others provide the fundamental research underlying assessments of the potential environmental and worker safety benefits of efficient electrification:

Air Pollutants and Toxics

- Assess potential electrification benefits for a particular service territory—including specific sources, activities, sectors and subsectors, electrification technologies, and air quality impacts.
- Provide tools (models) and assessments for EPRI members, regulators, and other stakeholders to aid air quality compliance, standards, asset management, and long-term planning.

Water and Ecosystems

- Energy-water planning for assessing environmental benefits and impacts of changes to generation/fuel mix and end-use electrification.
- Equip utilities and stakeholders to address electrification's benefits and impacts with respect to water availability and quality, the environment, ecosystems, and biodiversity.

Together with EPRI's much broader research efforts on electricity generation and delivery, these research, development, and demonstration efforts will provide a clearer view of the future of efficient electrification.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

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