Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050

Steven Nadel and Lowell Ungar September 2019 Report U1907

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Contents

About the Authorsiii
Acknowledgmentsiii
Executive Summaryiv
Introduction1
Methodology2
Efficiency Opportunity and Policy Packages
Appliance and Equipment Efficiency4
Zero Energy New Buildings and Homes5
Smart Buildings and Homes8
Home and Building Retrofits9
Electrification of Space and Water Heating in Existing Homes and Buildings12
Industrial Efficiency Improvements14
Light- and Heavy-Duty Vehicle Fuel Economy16
Reductions in Passenger Vehicle Miles Traveled (VMT)19
Reductions in Freight Transport Energy Use21
Aviation Efficiency Improvements22
Conservation Voltage Reduction and Reductions in Losses from Transmission and Distribution Systems)
Other Energy Efficiency Opportunities25
Energy Efficiency Resource Standard26
Analysis Results
Energy Savings27
Emissions Reductions
The Role of Electrification
Translating Our Results into Energy Productivity Terms

	Savings by Sector	30	
	Savings by Measure		
	Savings Relative to AEO 2011 Baseline	33	
	Policy Analysis Savings	33	
	Savings by Policy	35	
Concl	usions	37	
References			
Appendix A. Methodology Details			
Appendix B. Opportunity Analysis Details			
Appe	Appendix C. Policy Analysis Details		

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Executive Summary

KEY TAKEAWAYS

- Energy efficiency can cut US energy use and GHG emissions in half by 2050, getting the United States halfway to its climate goals.
- The United States can achieve almost all these savings, worth \$700 billion in 2050, under an ambitious set of government standards, investments, and other policies.
- The largest savings come from efficient and electric vehicles, industrial efficiency and decarbonization, transportation system efficiency, upgrades to existing buildings and homes, zero energy new buildings and homes, and appliance and equipment efficiency.

To avoid a climate change catastrophe, long-term strategies have called for reducing total US greenhouse gas (GHG) emissions by 80–100% by 2050. How much of the needed reductions can we achieve through energy efficiency? Previous studies, including by the International Energy Agency and the Natural Resources Defense Council, have found that efficiency measures throughout the economy can obtain nearly half these reductions. We decided to look more closely at US opportunities and policies that could reap the needed savings.

ENERGY EFFICIENCY OPPORTUNITIES

We modeled the combined impact of energy efficiency opportunities across buildings, industry, transportation, and the electric grid. We included measures that are ambitious but technically possible and also likely to be cost effective. We used the *Annual Energy Outlook* 2019 (*AEO*) as our baseline (adjusted to include more renewables and less coal in the electricity mix).





gy use by 49% (47 quadrillion Btus). The efficiency savings would reduce carbon dioxide (CO₂) emissions by 57% (2.5 billion metric tons, as shown in figure ES1). The emissions reductions are greater than the energy reductions because we included a shift from fossil fuel use to electricity for both vehicles and buildings (with electricity from a much cleaner power sector). When we include other

Figure ES1. Reduction in carbon dioxide emissions from combined opportunities

GHGs such as methane in the total, the efficiency savings reduce total 2050 GHG emissions by 49%.

As shown in Figure ES1, the top saving opportunities by sector are:

Efficient and electric vehicles. A shift to electric cars and trucks (80% of light- and 45% of heavy-duty vehicles) and continued fuel economy gains under new standards could cut vehicle carbon dioxide emissions in 2050 by about 50%.

Industrial efficiency and decarbonization. Strategic energy management and smart manufacturing could cut industrial energy use and emissions by 15%, and new technologies, industrial processes, and feedstocks (including electrification strategies) could save an additional 14%.

Transportation system efficiency. Less driving in cars and light trucks, improved freight system efficiency, and more efficient airplanes and aviation could reduce emissions by 30%, 25%, and 53%, respectively.

Upgrades to existing buildings and homes. Energy efficiency upgrades could cut energy use and emissions by about 18% for homes and 23% for commercial buildings, and smart control technologies could cut another 11% for homes and 18% for commercial buildings. Electrification of remaining loads adds an additional 13% in emissions reductions.

Zero energy new buildings and homes. Efficient design of new homes and commercial buildings, including electrification, and use of renewable electricity to meet average annual loads could cut their emissions by 80%.

Efficient appliances and equipment. Updated efficiency standards and growth in the ENERGY STAR[®] program could cut total home and building emissions by 13%.

UNLOCKING OPPORTUNITIES THROUGH POLICIES

We also looked at how much of the available savings could be achieved through an ambitious set of government energy efficiency policies. The policies we examined, which go far beyond current political and financial investment, could collectively spur almost all of the above savings: about 90% of the efficiency potential (42 quadrillion Btus and 2.2 billion metric tons of CO₂). Additional efforts would be needed to achieve the remaining savings.

The energy saved from government policies would be worth a total of about \$700 billion at the *AEO 2019*'s projected prices. We found significant savings in every fuel and in electricity — even after shifting most cars and about half of all trucks, homes, and commercial buildings to electricity. Figure ES2 shows the relative energy savings from the policies.

Achieving these savings will require expansion of energy efficiency efforts well beyond business as usual, including:

- Rapid upgrades to vehicle standards, building energy codes, equipment efficiency standards, ENERGY STAR specifications, and energy efficiency resource standards
- Substantial improvements to existing factories, homes, commercial buildings, and the electric grid and better management of energy use in all of them, spurred by government investment and requirements
- More mobility options and better management of freight and aviation energy use, including through user fees
- A switch to electric vehicles, equipment, and industrial processes (along with a more efficient and cleaner power sector)
- Greater investment in research and development for new efficiency options in every sector, especially improved industrial processes



Figure ES2. Allocation of energy savings by policy

Introduction

In recent years there has been a growing interest in long-term opportunities for reducing energy use and GHG emissions. *Long-term* is often defined as out to 2050. Former US president Obama submitted a "mid-century, long-term" strategy under the Paris Climate Agreement to reduce overall GHG emissions 80% by 2050 relative to the 2005 level (White House 2016), and a number of states and cities also have 2050 goals (Under2 Coalition 2019).

The American Council for an Energy-Efficient Economy (ACEEE) has previously released analyses of long-term energy efficiency opportunities. In 2012 we made our first estimate of energy efficiency opportunities out to 2050, finding that efficiency could reduce projected 2050 US energy use by 40–60% (Laitner et al. 2012). Similar savings were found in an analysis by the Rocky Mountain Institute (Lovins 2011). On the basis of these studies, ACEEE established a strategic goal to reduce projected 2050 US energy use by 50%.¹ In 2016 we prepared an analysis of energy savings and emissions reductions in 2040 from 13 opportunities (Nadel 2016b). We concluded that sufficient efficiency opportunities will be available by 2040 to put the United States on a path to reducing projected 2050 energy use by 50%. If we can achieve 50% energy savings from energy efficiency, energy-related GHG emissions would likely fall by at least that amount, making substantial progress toward the 2050 emissions goals discussed above.²

Other researchers have also found large energy efficiency opportunities that can make substantial contributions toward reducing GHG emissions. For example, the International Energy Agency, in its sustainable development scenario designed to reach the Paris Climate Agreement targets globally, found that energy efficiency can provide 44% of the needed emissions reductions in 2040 (IEA 2018). The Natural Resources Defense Council found that energy efficiency and electrification could achieve almost two-thirds of its goal of 80% emissions reductions in the United States relative to 1990 levels (Gowrishankar and Levin 2017).

Energy efficiency *opportunities* are technologies and practices that can be implemented to reduce energy use. Examples include installing LED lights, sealing building shells to reduce air leakage, using industrial software and management systems to reduce energy waste, designing trucks to reduce air resistance, and biking instead of driving. People often take these measures in order to save money on energy bills or for other benefits such as comfort, but large opportunities remain.

To take advantage of additional opportunities, we need durable government *policies* to spur greater private investment. Federal, state, and local governments set efficiency performance

¹We assess progress toward this goal in the discussion section of this report.

² The 80% emissions goal is for all GHG emissions relative to 2005 levels, while the 50% energy savings goal is relative to projected 2050 energy use. Using the *AEO 2019* and EIA estimates of 2005 energy-related emissions (EIA 2019a, 2019b), 2050 reference case energy-related emissions are projected to be 16% below 2005 levels. Emissions under the base and efficiency cases for this study are discussed in the Analysis Results section below.

standards, adopt labeling requirements and certification criteria, offer incentives and services, charge fees, provide loans, offer education and training, fund research and development, and manage their own energy use.

ACEEE has analyzed potential long-term impacts of many of these policies. In 2018 we looked at energy savings and carbon abatement out to 2050 from several energy efficiency policies, finding that they could cut energy use by more than one-third relative to the *Annual Energy Outlook 2018 (AEO)* projection, and by 50% if one includes the effects of policies that had recently been adopted (Ungar 2018).³

Since ACEEE's 2016 paper on opportunities, the US Energy Information Administration (EIA) has extended the *AEO* out to 2050, making improved analysis out to 2050 possible. Also, there have been substantial developments in the past few years on electric vehicles, intelligent efficiency (e.g., smart buildings and smart manufacturing), and industrial decarbonization strategies that should be included in an updated evaluation. We also think it would be useful to integrate our energy efficiency opportunity analyses with our policy analyses in order to better inform strategies going forward, hence this new report.

Methodology

For this project, we conducted two parallel analyses, one revising our 2016 opportunity assessment and the other revising our 2018 policy assessment.

The opportunity analysis is essentially a hybrid of a technical and an economic potential analysis.⁴ We looked at what is technically possible but only considered opportunities that are either cost effective now or likely to become cost effective. However we did not conduct a full economic evaluation, instead relying on a variety of previously published studies on cost effectiveness. We also recognize that achieving some of the savings (e.g., retrofits of 65% of all homes) may be challenging, even over three decades. For our opportunity analysis, we looked at 11 packages of energy efficiency technologies, practices, and programs that target specific end-use sectors. The opportunities and policies are listed in table 1, below, and details of each are discussed in the following section and in Appendixes B and C.

The policy analysis looks at how much of the savings potential that we found in the opportunity analysis could be achieved under a set of 11 government policies applied nationwide. Our investigation assumes that the policies are adopted and implemented nationwide on an aggressive timetable, but it does not consider whether they are implemented by local, state, or federal governments. The policies are designed to be reasonable and implementable and to benefit end users and society, but we did not try to assess political feasibility in the near term. Certainly the current federal Congress and administration would not adopt all of them. And some of the policies go well beyond what has been done in the past. Thus the policy side should be considered an aggressive but

³Some of the text below is adapted from those two papers and from Nadel 2018b.

⁴ For a detailed discussion of technical, economic, and achievable potential analysis, see Neubauer 2014.

achievable potential analysis. There are many more efficiency policies we could have included; we chose a limited number with high impact or close association with the identified opportunities.

Both analyses look at long-term savings above a business-as-usual projection; we only count savings beyond what have already been achieved and are expected to be achieved under existing policies and programs.⁵ Our reference case is a slightly modified version of the reference case in the *AEO 2019* (EIA 2019a). We estimate impacts on primary energy consumption including energy consumed in power generation and distribution and in mining, drilling, refining, and transportation of fuels (but we count renewable electricity as only the electricity produced). Our analysis includes direct rebound, the increase in use of an efficient product because of lower energy costs. We estimate carbon emissions reductions from saved electricity based on projected average emissions intensities. We discuss key details of our analysis in Appendix A.

Opportunity analysis	Policy analysis	
Appliance and equipment efficiency	Appliance efficiency standards and ENERGY STAR $^{\ensuremath{\$}}$ labeling	
Zero net energy (ZNE) new buildings and homes	Building energy codes	
Smart buildings and homes	Commercial building energy use benchmarking and standard	
Home and building retrofits	Home energy efficiency labeling and upgrade requirement for sale or lease	
Electrification of residential and commercial building space heating and water heating loads	Incentives for electrification of homes and commercial buildings	
Industrial efficiency improvements	Industrial efficiency programs and research	
Light- and heavy-duty vehicle fuel economy improvements including electrification	Light- and heavy-duty vehicle fuel economy and electric vehicle standards	
Reductions in passenger vehicle miles traveled (VMT)	Light- and heavy-duty VMT and congestion fees	
Reductions in freight transport energy use		
Aviation efficiency improvements	Airplane efficiency standard	
Conservation voltage reduction and reductions in losses from transmission and distribution systems	Regulation of conservation voltage reduction and of transmission and distribution losses	
Multiple	Energy efficiency resource standard	

Table 1. Measure packages examined in the opportunity and policy cases
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Efficiency Opportunity and Policy Packages

As discussed above, our analysis examined 11 packages of energy efficiency opportunities and 11 efficiency policy packages. The opportunities and associated policies are listed in

⁵ In our 2018 study (Ungar 2018), we estimated savings in 2050 from recent codes and standards to be 20% of the projected energy use for that year.

table 1. In many cases we examined a specific policy aligned with a specific opportunity. In some cases, policies are broader and address multiple opportunities, and in some cases more than one policy addresses individual opportunities.

Here, we discuss each of these opportunities and associated policies, including their scope, steps that might be needed to realize the savings from each, and key assumptions in our analysis. A cross-cutting policy is discussed at the end of the section.

APPLIANCE AND EQUIPMENT EFFICIENCY



Many types of appliances and equipment have made dramatic efficiency gains over the past four decades, driven in part by efficiency standards and labeling. Federal minimum energy efficiency standards currently affect more than 50 types of appliances, equipment, and lighting, ranging from residential refrigerators to industrial pumps. The US Department of Energy (DOE) estimates that standards already established (and therefore included in our *AEO 2019* baseline) will, on a cumulative basis, save more than 130 quads of energy through 2030, reducing energy bills by nearly \$2 trillion (DOE 2016).

In addition to minimum efficiency standards, the efficiency of new equipment purchases is affected by voluntary equipment efficiency specifications such as ENERGY STAR. ENERGY STAR has specifications on more than 50 different products, some of which are also covered by minimum efficiency standards. When the same product has both a standard and an ENERGY STAR specification, the standard covers all or most product sales, while ENERGY STAR affects only some sales, but at a higher efficiency level.

Achievement of the full savings potential will require various steps, including improved test procedures on some products (so that rated efficiencies better represent performance in the field, especially for "smart" products with adaptive controls); market introduction of an increased number of models at today's highest efficiency levels; efforts by manufacturers, distributors, utilities, governments, and large customers to promote these most-efficient products; and, ultimately, rulemakings by DOE to adopt new standards that require increased but cost-effective levels of efficiency for all products.

Savings Opportunity

We base our analysis on previous work on potential savings from new appliance efficiency standards. Our savings estimates involve dozens of products, with about 70% of the savings coming from a dozen products: residential water heaters, central air conditioners/heat pumps, showerheads, clothes dryers, refrigerators, faucets, and furnaces, as well as commercial/industrial fans, electric motors, transformers, air compressors, and packaged unitary air conditioners and heat pumps.

A 2016 report estimates savings for the next set of standards, covering those that should be set and take effect over the 2017–2029 period (deLaski et al. 2016). That report includes only savings that are technically feasible and already achieved in commercially available products and estimates annual savings in 2035 and 2050. We worked with the authors to estimate annual savings numbers with delayed effective dates for the early standards (none have been set to date). We also add savings from several proposed state standards discussed by Mauer, deLaski, and DiMascio (2017). We add an allowance for additional efficiency improvements in the 2030–2040 period (discussed in Appendix A) and deduct 8% for direct rebound effects (the weighted average of 10% for the residential sector and 5% for commercial and industrial). This analysis of potential may be conservative, as it does not include savings from larger systems (e.g., entire HVAC systems rather than individual components), and it does not include savings opportunities enabled by improved test procedures.

To estimate the additional savings from above-standard efficiency levels and products without standards, in our 2016 analysis we looked at annual savings data for minimum efficiency standards and ENERGY STAR over the 2005–2015 period and calculated a ratio (Nadel 2016b). Over those 11 years, average ENERGY STAR savings were 34% of the savings from minimum efficiency standards. However, as products improve in efficiency, opportunities for additional ENERGY STAR savings decline. Therefore for this report we take savings from new standards and add an additional 25% to include ENERGY STAR's potential impact (somewhat lower than the historic 34%).

Policies

For appliance and equipment efficiency, the opportunity savings estimate is based entirely on policies: minimum efficiency standards and ENERGY STAR. These savings are currently at risk – the current DOE leadership has stopped setting appliance standards, proposed process changes that would make it more difficult to set future standards, and repeatedly proposed to end funding for ENERGY STAR. However DOE says it will try to meet legal deadlines, Congress has rejected ENERGY STAR budget cuts, and process changes may well be modified by future administrations. Therefore, for this potential estimate, we assume that implementation of standards can quickly get back on track and that the long-term potential is still large.

ZERO ENERGY NEW BUILDINGS AND HOMES



Thousands of new homes and hundreds of commercial buildings have been built that produce at least as much energy as they use on an annual basis. Commonly labeled *zero energy buildings* (ZEB) or *zero net energy* (ZNE), they combine high levels of energy efficiency with solar or other renewable energy systems to meet average building loads over the course of a year. Related to ZEB are ultra-low-energy (ULE) buildings. By reducing energy use, ULE construction makes ZEB much more feasible and is sometimes labeled "ZEB

ready." The New Buildings Institute has documented nearly 500 commercial buildings in the United States that, as of late 2017, were either verified ZEB, not-yet-verified ZEB, or ULE (NBI 2018). The Net-Zero Energy Coalition has identified more than 6,000 ZEB or ZEB-ready homes and residential buildings in the United States that collectively contain nearly 14,000 housing units (NZEC 2018). The positive economics of ZEB has been documented in a variety of studies, including Corvidae, Gartman, and Peterson (2019) for homes and NREL (2014) for commercial buildings. As the number of ZEB homes and buildings increases, we would expect the economics to improve as designers and builders gain experience and develop improved practices.

Several efforts are targeting the adoption of ZEB (or ULE) building energy codes by around 2030; for example, such targets are envisioned by California, Canada, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, for its stretch code) (California Energy Commission 2018; National Research Council Canada 2018; ASHRAE 2008). Many cities are adopting stretch codes with greater efficiency (if short of ZEB or ULE levels), and Massachusetts and New York State have issued such codes for their cities to adopt (NBI 2019). However the national model energy codes, especially for homes, are progressing slowly.

In addition, several utility and nonutility program administrators have specifically aimed programs at promoting ZEB construction locally. Notable examples include an Energy Trust of Oregon program for commercial buildings and a New York State Energy Research and Development Authority program for new single-family and multifamily homes (York et al. 2015a).

Amann (2014) and Perry (2018) discuss obstacles to the goal of widespread ZNE use by 2030 and suggest a combination of R&D, implementation, and building code strategies for reaching the target. R&D needs include development of workable system performance metrics and of outcome-based code approaches that look at how much energy buildings use once occupied. Implementation strategies include building rating and labeling, public sector leadership, stretch codes and green codes, beyond-code guidelines, incentives, and valuing efficiency in financial transactions.⁶ Amann suggests leads for specific activities and identifies specific items for national model codes to address, with some items to be taken up in the next code cycle, some in the 2020s, and some not until 2030. To reach the goal, all of these strategies must contribute in a comprehensive effort.

Savings Opportunity

For our opportunity savings estimate, we assume that 90% of new construction by baseline energy use in 2040 and beyond achieves ZEB or ULE performance, with the savings ramping in over the 2031–2040 period. Based on data from the New Buildings Institute, for

⁶ *Stretch codes* are codes adopted by local jurisdictions that exceed statewide codes. *Green codes* include many environmental features in addition to energy efficiency and are typically voluntary, although a few jurisdictions have adopted mandatory green codes. Valuing efficiency may mean including efficiency features in building appraisals and considering both energy and mortgage costs in mortgage underwriting decisions.

new construction we assume 70% energy savings relative to reference case efficiency levels, with the remaining 30% coming from a mix of on-site or off-site renewable energy systems (C. Higgins, research director, New Buildings Institute, pers. comm., July 8, 2019).⁷ The 10% of new construction not affected is either in locations or in building types, such as hospitals, for which energy intensities are high and ZNE performance is challenging. With loads this low in ZEB or ULE buildings, we assume most buildings will install heat pumps, saving the cost of including gas in the building. For highly efficient new construction, even in very cold locations such as New England, heat pumps can generally supply all needed heat (Nadel 2018a). For residential and commercial new construction between 2020 and 2030, we use the new construction savings estimates developed by York et al. (2015a), resulting in 24% commercial and 22% residential savings ramping in starting in 2020. For the reference case we assume that average new home energy use and new commercial building energy intensity would be the same as in the building stock each year; although new homes and buildings are more efficient, new homes are larger, and new commercial buildings have higher loads. Because most of the savings are from ZEB buildings, we assume renewable energy systems would be sized to cover typical rebound effects, and rebound is already included in the savings described above.

Policies

For our policy analysis we assume rapid model energy code improvements, quick adoption across the country, and effective compliance, but without specific ZEB construction requirements. We assume that future model building energy codes (International Energy Conservation Code for homes and ANSI/ASHRAE/IES Standard 90.1 for commercial buildings) would achieve about 10% energy savings in each three-year code cycle; that the codes would be implemented nationwide over five years; and that loss of savings due to noncompliance would start at 20% for homes and 50% for commercial buildings, decreasing by 10% each year – all significant advances over the status quo. The *AEO 2019* baseline case does not assume future code improvements but does include gradual efficiency gains; therefore we subtracted a bit from the above savings, especially for continued implementation of recent savings in 90.1 (see Appendix B for details). The result is that savings due to codes compared with the baseline rise to 61% in 2050 for homes and to 53% in 2050 for commercial buildings. We reduce the savings estimates for codes to account for direct rebound (10% in homes, 5% in commercial buildings).

⁷ The shift to renewable energy for the remaining energy use does not affect our energy savings estimates but is reflected in our GHG savings calculations, with half of this renewable energy assumed to be on-site and not registering in the electric grid, and half assumed to be off-site (either community-level or utility-level systems) and included in the increased percentage of electricity we assume to be from renewables. Although *AEO* does not include rooftop solar in primary energy use, we do not count that as energy savings from efficiency.

SMART BUILDINGS AND HOMES

Energy	
savings	
3.2	

CO₂ emission reductions

125

quadrillion million metric tons BTUs

One large class of system improvements is *intelligent efficiency* – that is, the use of information and communications technology (ICT), access to real-time information, and smart algorithms to help optimize energy-using systems (Elliott, Molina, and Trombley 2012). A simple example of an intelligent efficiency measure is a learning thermostat (e.g., Nest or ecobee) that monitors home temperature and occupancy, weather, and other parameters and finds ways to improve heating and cooling system operation after learning a household's patterns (e.g., when people are home and which temperatures they like).

Rogers et al. (2013) discuss a variety of needed steps to promote realization of these savings. These steps include adopting common communication protocols so that systems from different vendors can talk to each other; developing systems for using ICT to document savings so that utility and other incentive programs can include intelligent efficiency approaches; better educating home and building owners on intelligent efficiency capabilities and benefits; documenting best practices from early projects; and demonstrating projects in promising market niches that lack documented results. Incentive programs – such as cost-sharing of smart building service fees to encourage building owners to take advantage of these emerging services – can help accelerate progress (Rogers 2018). Continued R&D support is also needed, particularly for smart energy management systems for smaller buildings. Many utility programs are providing incentives, especially for learning thermostats, and the Smart Building Acceleration Act (H.R. 2040) would establish a research and development program at DOE and encourage deployment in federal buildings.

Savings Opportunity

For homes, King (2018) documents ways to achieve 17% average whole home savings from smart strategies. There are additional available savings from providing real-time energy use feedback (York et al. 2015a). The cost effectiveness of all of these strategies has not been documented, but York et al. (2015a) provide data on how savings from smart thermostats cost an average of about 3 cents per kWh saved. For our analysis, we assume 15% average whole home savings. Obtaining 15% average savings will require improved technology that can be installed easily and at moderate cost. We gradually ramp up to 80% penetration of these measures by 2050. More sophisticated systems used in commercial and industrial buildings offer even greater reductions in energy use. Rogers et al. (2013) estimate a 28% average electricity savings available in commercial buildings (weighted average across all end uses). King and Perry (2017) estimate that smart building systems can reduce building energy use by 30% or more. York et al. (2015a) find typical costs of 2–3 cents per kWh saved. For our analysis, we round down to 20% savings across all fuels. Kramer et al. (2018) find more than 20% savings in several buildings with energy management information systems that have been optimized over a three-year period. In our analysis, smart building savings apply to a gradually growing share of the building stock, reaching 95% in 2050. We estimate that direct rebound will reduce residential savings by 10% and commercial savings by 5%.

Policies

For our policy analysis, we include three broad policies that would spur deployment of smart homes and buildings as well as home and building retrofits: a commercial building standard based on energy use benchmarking, a standard based on a home energy rating for homes that are sold or rented, and an energy efficiency resource standard for utility energy efficiency programs. We discuss the first and second in the next section and the third in a separate section below.

HOME AND BUILDING RETROFITS



A substantial portion of the homes and commercial buildings that will be standing in 2050 have already been built. This reality makes retrofitting existing buildings critically important. Residential programs such as Home Performance with ENERGY STAR can reduce energy use by 20–30% (Belzer et al. 2007; Liaukus 2014), and retrofits saving 50% or more have been documented (Cluett and Amann 2014). Similar savings are possible in commercial buildings. For example, a retrofit of the Empire State Building in New York was projected to reduce energy use by 38% (Harrington and Carmichael 2009), but performance data from the first three years show even greater savings (C 40 Cities et al. 2014). Likewise, a study on 10 deep energy retrofits of federal buildings found average savings of 38%, with savings in individual projects ranging from 18–100% (Shonder 2014).⁸

However participation in retrofit programs is generally low. For example, Neme, Gottstein, and Hamilton (2011) and York et al. (2015b) find that the highest participation rates for residential comprehensive retrofit programs across broad numbers of customers approached but did not reach 2% of those eligible each year. Some geographically targeted

⁸ Most of the savings are from energy efficiency improvements, but the projects with very large savings (e.g., 60% and 100%) also include solar systems.

or single-measure programs had higher participation rates and provide lessons on how to increase participation rates in the future. Furthermore, only a fraction of retrofits come close to the energy savings level seen in the Empire State Building.

We need to improve our building retrofit efforts to go wider (involving more buildings) and deeper (achieving more savings per building). To achieve this, we will need multiple strategies, including building energy use transparency (e.g., benchmarking energy use, rating energy efficiency, and access to energy use data), contractor training and certification, home and building owner education and technical assistance, incentives and financing for energy efficiency improvements, continuing R&D efforts to identify better and easier ways to improve the efficiency of existing buildings, and improved program designs to increase participation rates and savings per home. Cluett and Amman (2016) discuss a variety of promising strategies. Low-income households and communities are a particular challenge, as they rarely have the funds to conduct retrofits. Increased grant funding will be needed, complemented with long-term financing that can be used by some moderate-income households.

The US Environmental Protection Agency's ENERGY STAR Portfolio Manager is a userfriendly tool used to benchmark a commercial building's actual energy use against that of similar buildings. It gives a score of 1–100 that is based on percentile (e.g., a score of 75 is supposed to mean a building is more efficient than 75% of similar buildings). Forty percent of commercial building space has used the tool.⁹ Benchmarking energy use can help to get the attention of building owners and can motivate capital and operational improvements. Many cities, including New York, Los Angeles, and Philadelphia, and two states, California and Washington, require large commercial (and often multifamily) buildings to benchmark their energy use and publicly disclose the results. The cities have typically found 3–8% energy savings in buildings in the first few years (Mims et al. 2017).

For homes DOE has developed a Home Energy Score tool that gives an efficiency rating of 1–10 based on detailed information about the home – not actual energy use data – collected by a trained assessor. The tool also gives suggestions for improving the efficiency. The scores are loosely based on percentiles such that in each region 50% of homes should have a score of 1–5 and 50% a score of 6–10. (The 15% of homes with the highest estimated energy use should have a score of 1, the best 10% a score of 10.) More than 100,000 homes have been scored to date.¹⁰

A few jurisdictions have begun to implement efficiency requirements for existing buildings, which promise much greater savings. Washington, DC, New York City, and Washington State recently passed laws for large commercial and some multifamily buildings. In Washington, DC, buildings must meet a standard that will be set no lower than the median ENERGY STAR score, or else reduce energy use by at least 20%, starting in 2026 (DC

⁹ See <u>www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager</u> and links for more information on ENERGY STAR Portfolio Manager. See <u>www.buildingrating.org/</u> for more information on local and state policies.

¹⁰ Detailed information is available at <u>www.homeenergyscore.gov</u>.

Council 2019). The standard is to be updated every five years. The Washington State law is somewhat similar (Washington State Legislature 2019). New York City set carbon emissions intensity standards starting in 2024 that are expected to result in 26% average energy savings in covered buildings; the standards can also be met with local renewable energy credits or offsets (Urban Green Council 2019). Other policies have focused on multifamily residences. Boulder, Colorado, has a regulation requiring that multifamily buildings built before mid-2001 earn a specified number of energy efficiency points by 2019 before they can be rented (Boulder 2018).¹¹

Similar regulations are being adopted internationally. In the United Kingdom, owners of rental apartments were required to upgrade to an E level on Europe's A–G building efficiency scale by 2018.¹² And France has a law requiring existing homes (including single-family) to meet steadily more stringent energy efficiency requirements, with the targets set many years in advance. Under the French law, all F- and G-rated homes must be retrofitted to at least the E level by 2025 before they can be sold or rented. In this way, building owners have many years of lead time to determine when and how to upgrade their buildings (BPIE 2015). France also has a longer-term goal of requiring an A rating by 2050 and is discussing the possibility of interim dates by which D, C, and B ratings might be required.¹³ Implementing regulations for the early tiers still must be developed; the latter goals do not yet have the force of law.

Savings Opportunity

For our savings estimate, we assume 30% whole building energy savings on average. These savings are applied to energy use after subtracting savings from measures discussed in prior sections, thereby avoiding a double counting of savings. We estimate that 65% of homes will be gradually retrofit by 2050 (about 2% per year) and that 80% of commercial building floor area will be gradually retrofit as owners periodically update large buildings to retain their market position.¹⁴ We do not include electrification in these savings estimates; electrification is treated separately, as discussed later in this paper. We reduce these savings estimates to account for direct rebound (10% in homes, 5% in commercial buildings).

Policies

For this analysis we assume that commercial buildings with low benchmarks would be required to increase efficiency to bring their scores up. They could do this through a combination of building retrofits, improved energy management, and behavior changes. Loosely based on the law in Washington, DC, we assume the policy would affect buildings of more than 50,000 square feet in 2022, 25,000 square feet in 2024, and 10,000 square feet in 2027, taking percentages of total commercial energy use from the 2012 Commercial Building Energy Consumption Survey (CBECS) (EIA 2016b). We assume that buildings below an

¹¹ Buildings built after mid 2001 need to meet building energy codes that provide similar savings.

¹² See <u>www.rla.org.uk/landlord/guides/minimum-energy-efficiency-standards.shtml</u>.

¹³ See <u>www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000031044385&categorieLien=id</u> (in French).

¹⁴ Alternatively, the same commercial building savings would be achieved by deep retrofits that save an average of 50% of energy use in 48% of buildings.

ENERGY STAR benchmark of 50 would need to reach a score of 50 or reduce energy use by 20%, ramped in over five years, and then improve their score by at least 10 points or achieve an additional 20% savings every 10 years (hence a score of 70 or combined savings of 49% by 2047–2052). We roughly estimate the impact using the curve of average energy use by ENERGY STAR score for office buildings (ENERGY STAR 2019, fig. 5). The result is savings of 12% of covered energy use under the first standard, 23% under the second, and 32% under the third when fully phased in. We assume that half the savings from appliance standards and ENERGY STAR in commercial buildings would contribute to meeting this standard. But any direct rebound effect would require additional savings to meet this performance standard.

We also include a standard for homes based on the home's estimated efficiency rather than its actual energy use and applying only to homes that are rented or sold. We assume a policy requiring all homes that change occupants due to rental or sale to be brought up to a minimum Home Energy Score: 2 starting in 2025, increasing by 1 every five years thereafter, except that no home ever has to increase its score by more than 3 (thus in 2045, when the minimum score is 6, a home that started as a 1 would need to be brought up only to 4). We estimate the relative energy use by bin by taking a simple average of the bin caps for the 996 Home Energy Score regions, and then calculate the savings from bringing homes from the middle of each bin to the required cap. We then calculate savings for rented and owned homes separately (neglecting shifts between the pools), using Residential Energy Consumption Survey data for relative energy use and assuming 5.9% annual sales of owned homes (based on National Association of Realtors sales data for 2016–2018), and 20% annual turnover of rented homes (a conservative blended estimate for apartments and single-family homes). We account for homes turning over multiple times, assuming no correlation between turnover year-to-year. The potential savings for requiring efficiency at the bin 2 level is 2% of total residential energy use, rising to 16% for bin 6, but because of slow turnover the savings for owned homes barely reach half of that. We reduce savings by 10% to account for rebound.

ELECTRIFICATION OF SPACE AND WATER HEATING IN EXISTING HOMES AND BUILDINGS



With the electric grid steadily getting cleaner and reducing emissions, the electrification of space and water heating is a decarbonization strategy that is becoming more viable. Current technology options for space and water heating in buildings include electric resistance heat, heat pumps (primarily air-source but also ground-source), and either condensing or non-condensing use of fuels (natural gas, oil, or propane furnaces or boilers). If high-efficiency heat pumps use electricity from low- or no-carbon generation, they can achieve substantial energy savings as well as emissions reductions. Converting to heat pumps at the time an existing air conditioner, furnace, or boiler needs to be replaced often will save money on a life-cycle cost basis, particularly relative to oil and propane, but also relative to natural gas in warm climates. For the North, further work is needed to improve the availability and

performance of cold-climate heat pumps. Even in the South, at current natural gas prices, a recent study found that the economics of conversion may not be compelling to consumers; while there are life-cycle cost savings, payback periods are often long (Nadel 2016a, 2018b). The Rocky Mountain Institute draws a similar conclusion but also finds heat pumps generally cost effective in new construction (Corvidae et al. 2019). There have not been many studies on electrification in the commercial sector, although Kim et al. (2017) find energy and economic savings from use of variable refrigerant flow (VRF) systems in medium-size office buildings.¹⁵

To realize these savings, near-term efforts should focus on market niches where electrification may be more attractive, and on improving the availability, performance, and cost of cold-climate heat pumps. Potential near-term market niches include new construction (benefiting from the avoided cost of installing gas service), particularly in the South; homes without air-conditioning but where air-conditioning is desired (including many homes with boilers); and homes and buildings using expensive fuels such as fuel oil and propane. To spur use of heat pumps in new construction, building codes could favor such use, and/or utility commissions could consider limitations on extension of gas distribution systems to new areas. Incentives to buy high-efficiency heat pumps are important, especially when homeowners replace equipment at the end of its life. Incentives for induction stoves can help homes to go "all electric," avoiding the need for gas lines in new development. However rules against the funding of fuel switching prevent such incentives in many states. To spur substantial conversions of homes and buildings now using natural gas, a price on carbon and/or incentives for conversions to heat pumps will be needed to help improve conversion economics and drive retrofit activity.

Savings Opportunity

For our analysis of electrification of existing homes and buildings, we use conversion rates (percentage of buildings converting from fossil fuel systems to electric systems) from a highelectrification scenario developed by NREL. This scenario includes gradual electrification in residential and commercial sectors by 2050 by converting about 50% of residences and 45% of commercial buildings. We heavily weight these conversions to buildings using oil and propane, and we increasingly also include buildings using natural gas in the 2030s and beyond. Energy savings from electrification will vary with the climate and building. We used estimates of average US primary energy savings of 21% for homes (Nadel 2018a) and 28% for commercial buildings (Kim et al. 2017). These estimates are based on current heat rates; as heat rates improve the primary energy savings increase, a factor we take into account for homes.¹⁶

¹⁵ Use of renewable natural gas is another potential route to decarbonizing gas uses, but the amount of renewable natural gas potentially available is likely to be much lower than current natural gas use. If renewable natural gas supplies are limited, use of renewable natural gas should probably first go to end uses that will be very difficult to serve with electricity, such as high-temperature industrial processes, some industrial feedstock uses, and long-haul trucks.

¹⁶ We do not make a similar adjustment for commercial buildings because commercial building savings data are very limited and not solid enough to justify adjustments.

To account for overlap with all of the measures discussed previously, we subtract savings from prior measures that affect building space and water heating before analyzing electrification. As a result, the loads to be electrified are substantially smaller than if electrification were applied to current loads. Applying efficiency measures first reduces the cost of electrification (smaller heat pumps are needed) and also improves the ability of heat pumps to serve loads while maintaining comfort on very cold days. We do not assume any rebound as energy cost savings are relatively small.

Policies

For our policy analysis we assume that a combination of the rules, fees, and incentives discussed above in this section spur the fuel switching.

INDUSTRIAL EFFICIENCY IMPROVEMENTS



The industrial sector has been steadily improving in energy intensity.¹⁷ Industrial energy use per dollar of shipment value declined 38% over the 1980–2013 period (Nadel, Elliott, and Langer 2015). This is a compound average annual decline of about 1% per year. However these improvements have been irregular, driven by changes in energy prices and other factors. EIA projects that over the 2019–2050 period, this metric will continue to decline by 1.0% per year (EIA 2019a). These reductions in energy intensity result from changes in the processes used to produce goods, optimization of these processes, and shifts in the mix of products we produce domestically. International trade (i.e., which products are produced overseas and shipped to the United States) also plays an important role.

Savings Opportunity

Given global pressures to reduce GHG emissions and compete internationally, we think more rapid intensity improvements can be achieved, building on the progress made in recent decades. Specifically, we model three steps, with savings estimates adapted from Rissman et al. (2019):

1. *Expanded implementation of energy efficiency technologies and practices that exist today but are underutilized.* This element would be grounded in wider adoption of strategic energy management (SEM) by industrial facilities, which our research shows creates an environment that encourages implementation of other energy efficiency and decarbonization technologies and practices (for more on this, see Rogers, Whitlock, and Rohrer 2019). This element also includes expanded deployment of smart manufacturing (applying intelligent efficiency strategies in the industrial sector),

¹⁷ For the industrial sector, we use energy intensity rather than energy efficiency, since industrial output varies significantly year-to-year in response to changing economic forces.

including optimization of the motor, fan, pump, and compressed air systems that account for more than half of electric energy consumption in industrial facilities. Therkelsen et al. (2015) finds that an SEM program saved an average of 11% of energy use in 10 disparate factories by the second year. Rogers et al. (2013) estimate that smart manufacturing could reduce industrial energy use by about 20%. And Elliott and Nadel (2003) estimate 20–50% savings in fan and pump system energy use from system optimization. We model this set of measures as 20% energy savings per facility, gradually ramping up on a straight-line basis to 80% of facilities by 2050.

- 2. Accelerated implementation of underutilized and emerging industrial technologies in the near term, driven by targeted commercialization research as well as steps to aid early adoption of these technologies. Technology examples include submerged combustion melting, inert anodes for aluminum production, and low-carbon cements and steelmaking. We estimate a further 15% savings from these technologies, with initial applications in 2025, ramping up to 65% of facilities by 2050.
- 3. Development and implementation of medium- and long-term emerging technologies that make more fundamental changes in processes and products. These changes would include process electrification; industrial carbon capture, utilization, and sequestration; shifts to bio-based feedstocks; and use of hydrogen as both a fuel and a reactant in many key manufacturing process applications. We also need to fundamentally rethink the products we use from an economy-wide perspective, changing the products industry creates in order to minimize their global warming potential on a life-cycle basis. For example, can engineered wood products replace steel and cement in buildings? We estimate 15% savings from these technologies, with initial applications in 2035, ramping up to 50% of facilities by 2050.

Note steps 2 and 3 are combined as "Industrial Emerging Technologies" in results below. We estimate direct rebound effects of 5%, as lower energy costs could translate into slightly lower product costs and hence slightly higher demand.

To achieve these savings, improvements — including those that take advantage of R&D advances — must be made in industrial processes at opportune times, such as when facilities are periodically modernized. We also need to provide risk sharing for industrial firms as they make major new investments in new process technologies and products. Manufacturing firms are by nature capital-intensive and often low-margin businesses, so they have limited ability to take on additional risk without public or private sector mechanisms managing new investments that replace existing assets (T. Heidel, principal, Breakthrough Energy Ventures, pers. comm., April 19, 2019). We also need to remain attentive to labor dislocations that inevitably occur as we transition to a new, low-GHG industrial environment.

Policies

Because governments can play a crucial role, we assume the full savings from the three steps could be achieved through policies. DOE has made key contributions to promoting strategic energy management, including work on the international energy management standard, ISO 50001, an add-on certification called Superior Energy Performance, and an

easier self-guided approach called 50001 Ready.¹⁸ Further incentive programs through utilities or the federal and state governments would spur faster adoption. DOE also is helping with smart manufacturing, including through the Clean Energy Smart Manufacturing Innovation Institute.¹⁹ The Smart Manufacturing Leadership Act (S. 715/H.R. 1633 in the 116th Congress) would expand federal assistance. DOE's Industrial Assessment Centers also help bring SEM and smart manufacturing to smaller plants.²⁰ DOE's Save Energy Now program also provided effective energy audits in large plants (Wright et al. 2010). An expanded version could bring newer technologies to the largest energy users.

To achieve the savings in steps 2 and 3, further policies are needed. Federal funding for research and development has played a key role in industrial efficiency advances. Renewed focus on cooperative research with energy-intensive industries will be needed to develop, demonstrate, and commercialize the process changes needed. Assistance is necessary not just to invent new technologies and practices but to test them and promote their early deployment. Policies can also help focus corporate management attention. One model that has been implemented in some European countries is the use of long-term agreements under which companies commit to specified energy savings in return for tax incentives (Waide 2016).

LIGHT- AND HEAVY-DUTY VEHICLE FUEL ECONOMY



The fuel economy of US light-duty vehicles — that is, cars and light trucks such as minivans and many SUVs and pickup trucks — has increased substantially in recent years, driven by increases in federal fuel economy standards triggered by the Energy Independence and Security Act of 2007 (EISA). EISA also mandated that federal agencies develop fuel economy standards for heavy-duty vehicles, which range from heavy pickup trucks to 18-wheelers. The first standards took effect in 2014 and were extended in 2016. Under these two rounds of standards, new heavy-duty vehicle fuel use is projected to decrease by an average of 37% by 2027, relative to 2010 vehicles (Khan 2016).

Now light-duty electric vehicles (EVs) are starting to take off, with many new models being introduced each year, including several with ranges exceeding 200 miles and priced under \$40,000 (e.g., the Chevrolet Bolt and Tesla Model 3). Electric vehicles are generally more

¹⁸ See <u>www.energy.gov/eere/amo/50001-ready-program.</u>

¹⁹ See www.cesmii.org.

²⁰ See www.energy.gov/eere/amo/industrial-assessment-centers-iacs.

efficient and have lower emissions than gasoline or diesel internal combustion engine (ICE) vehicles (see figure 1 below). Thus operating costs are typically lower for EVs than for ICE vehicles (Logtenberg, Pawley, and Saxifrage 2018). Recent projections are that EVs will reach parity in terms of annual cost of ownership in 2022–2024 (Deloitte 2019).²¹ And according to one optimistic estimate, EVs could reach first-cost parity with large ICE vehicles in Europe as soon as 2022 (Bullard 2019). Forecasts of future market share are being revised upward (Lacey 2017). Forecasts by Bloomberg New Energy Finance (BNEF) and Energy Innovation estimate that EVs may account for 35% of new US light-duty vehicle sales by 2030 and 65% by 2050 (Rissman 2018).

Achieving these gains will require continued efforts to extend the range and bring down the cost of EVs (with battery costs particularly important). Also, many more public charging stations will be needed, particularly for multifamily buildings, in low-income communities, for ride-sharing vehicles, and along interstate highways. Utilities are increasingly playing a role in the expansion of charging infrastructure, with utilities and their customers typically paying to bring electric service to charging locations and private companies installing the charging stations themselves (Khan and Vaidyanathan 2018). Finally, fuel economy (CAFE) and GHG emissions standards for vehicles can be regularly updated; such updates will continue to drive fuel economy improvements including increased sales of EVs.



Figure 1. Comparison of two EVs, a hybrid car, and the average new vehicle on fuel economy and emissions per mile, based on US government fuel economy and emissions labels for 2018 vehicles. Our adjustments for upstream system losses are based on a 45% efficient power plant and 28% upstream energy losses for gasoline (the latter derived from Argonne National Laboratory's GREET 2018 model). GHG emissions are derived by ACEEE from GREET 2018 using the current national average generation mix.

Savings Opportunity

For our light-duty vehicle estimates, we assume substantial growth in the market share of electric vehicles as well as continued improvements in the fuel economy of petroleum-powered vehicles. We assume that EVs will represent 50% of new vehicle sales by 2033 (per the BNEF forecast) and will continue to ramp up market share until reaching 80% in 2042 (with the remaining 20% hard to electrify). As EVs shift away from premium vehicles, we assume the efficiency will start at 3.4 miles/kWh and increase by 2% each year. For the

²¹ Annual cost of ownership assumes that the vehicle purchase is financed with a loan and includes annual operating costs.

remaining ICE vehicles, we assume that the current 2025 fuel economy standards will be implemented and that fuel economy will improve 4% per year from 2025–2030 and 2% per year thereafter. These assumptions modestly exceed the midrange case but fall well short of the optimistic case estimated by the National Research Council (2013). This National Research Council study finds that fuel economy improvements of this magnitude will be cost effective.

For our analysis of medium- and heavy-duty vehicles, we assume a gradual increase in EVs, ramping up to 50% of the stock by 2050. Gao et al. (2018) estimate energy savings for 10 types of commercial vehicles, with the primary energy savings averaging 36% (using Gao's electricity sector assumptions) but ramping up to 45% by 2050, adjusting for our assumptions about improving power sector heat rates. For ICE vehicles, we assume a 2% annual improvement in fuel economy beginning in 2028 (the first year of the next round of fuel economy standards). This level of improvement was found to be achievable and cost effective through 2035 by the Global Fuel Economy Initiative and the International Council on Clean Transportation (Delgado et al. 2016). Substantial additional opportunities in engine efficiency, aerodynamics, and automation would enable continued improvement through 2050.

Based on published estimates, we incorporate 10% direct rebound for light vehicles and 8% for heavy vehicles (Nadel 2016c; EPA and NHTSA 2016).²² For the switch to EVs we assume that the net cost savings of electricity per mile versus gasoline or diesel causes a corresponding increase in the amount of driving and hence electricity use; because the percentage cost savings is large, we assume a nonlinear rebound based on constant price elasticity.²³

Policies

Achieving these savings will require continual improvements in the federal fuel economy standards, as well as continued R&D efforts (e.g., the DOE SuperTruck program) and expanded efforts to promote EVs and other high-efficiency vehicles such as hybrid trucks.²⁴ As noted above, growth in EVs will require large expansions in charging infrastructure. Improved electric rate structures will be needed to encourage charging during off-peak periods while not unduly penalizing vehicles that must charge during peak periods.

Our policy analysis assumes the full savings for light-duty and heavy-duty vehicles. As described above, fuel economy and GHG emissions standards have driven rapid fuel economy improvements in recent years. California's zero emission vehicle requirements

²⁴ For more information on the SuperTruck program, see

²² The 8% figure is a weighted average based on fuel consumption; EPA and NHSTA estimate 15% for vocational vehicles and 5% for tractor trailers.

²³ Research is needed that estimates the rebound for the switch to EVs from actual EV use. Rebound rates derived from elasticities tend to overly simplify interactions that depend on many factors including changes to the product other than its energy use. Thus they can be too high (Gillingham 2016). The rebound approach used here results in a 12–15% increase in use for light-duty EVs and a 7–9% increase for heavy-duty EVs.

energy.gov/sites/prod/files/2016/06/f32/Adoption%20of%20New%20Fuel%20Efficient%20Technologies%20fr om%20SuperTruck%20-%206-22-16%20%28002%29.pdf.

(also adopted by nine other states), along with federal tax incentives and state purchase incentives, have been important drivers for EVs and plug-in hybrid vehicles. Although the current federal administration is poised to issue a rule to weaken light-duty vehicle standards (including state standards), that attempt will be challenged by California and other states in court. Strengthening these policies and support for charging infrastructure could achieve the savings described above.

REDUCTIONS IN PASSENGER VEHICLE MILES TRAVELED (VMT)



New mobility options, especially in urban areas, could reduce many people's need to drive or own a personal vehicle over time. These options include ride sharing, car sharing, improved public transit systems, and on-demand flexible-route services. Continued revitalization of US urban cores and inner suburbs both supports and benefits from these developments. With the increase in compact growth patterns and pedestrian- and bikefriendly streets, residents will rely on nonmotorized modes to meet more of their work and nonwork mobility needs. On-demand shared-use vehicle services that are reliable and affordable will allow many households to forgo vehicle ownership altogether. These changes should permit a substantial decline in VMT overall. Such a result is not guaranteed, however, especially if these mobility services replace public transit and provide singleoccupant vehicle services to children and others who do not currently drive. Telecommuting and e-commerce can also reduce vehicle use, although some of the reductions will be offset by home office and delivery firm energy use.

California is establishing a policy framework that shows one way VMT reductions might be achieved, providing a potential model for other states and communities. Under S.B. 375, the Sustainable Communities and Climate Protection Act of 2008, and with guidance from the California Air Resources Board, metropolitan planning organizations (MPOs) covering 95% of the state's population adopted plans in 2018 to reduce VMT per capita from 2005 levels by 13–19% by 2035 (California ARB 2018). The primary mechanism for achieving S.B. 375 targets is the coordination of transportation and land use planning. The MPOs have prepared Sustainable Communities Strategies for inclusion in their Regional Transportation Plan updates, spelling out land use, housing, and transportation measures that will reduce the number and length of car trips projected to occur in each region. More recently California passed S.B. 1014 (2018) to create a Clean Miles Standard, a GHG emissions standard based on passenger miles for services such as Lyft and Uber. Besides using EVs, these services can meet the standard by more efficient dispatch and increased ride sharing.

There also is a lot of discussion of VMT and congestion fees as a funding mechanism for needed infrastructure investments. The primary funding source for federal investment in roads and transit is the gasoline tax. But the federal gas tax (18.4 cents per gallon) has not increased since 1993 even as inflation has raised prices overall by about 75%. Thus there is a chronic shortage of infrastructure funds. In addition, there is concern that the shift to EVs

and increasing fuel economy will shrink gas tax revenues even more in the future. One solution would be to charge a fee based on VMT, perhaps a fee that varies with the amount of congestion. Oregon has experimented with a voluntary road usage charge, OReGO, though in Oregon's case the VMT fee is in lieu of gasoline taxes.²⁵ London has instituted and New York City is planning a fee to drive downtown on weekdays, and many toll roads have dynamic tolls based on demand, in part to keep traffic flowing.

No similar policy framework currently exists at the federal level. However the US Department of Transportation (DOT) did adopt regulations in 2017 directing federal transportation funding recipients – including state DOTs and MPOs – to set targets for mobile source GHG emissions and measure performance toward meeting those targets.²⁶ This regulation was repealed in 2018 following the change in federal administration.²⁷ Establishing such targets would help achieve the substantial VMT reductions we model.

Savings Opportunity

DOE's Transportation Energy Futures project estimated that, by 2050, energy demand of light-duty vehicles could be reduced by about 20% through changes to the built environment (higher densities, mixed-use development, walkable neighborhoods) and other trip-reduction strategies (NREL 2013). Vaidyanathan (2014) estimates a potential 13% reduction in light-duty fuel use by 2030 from six strategies based on ICT, including car sharing, real-time transit information, and vehicle-to-vehicle communications. Fulton, Mason, and Meroux (2017) discuss additional strategies for optimizing urban transportation. Combining the NREL and Vaidyanathan estimates and adjusting for modest overlap, we estimate that VMT can be reduced by 30% in 2050 relative to the *AEO 2019* reference case. This savings estimate incorporates direct rebound effects.

The *AEO 2019* projects an average annual VMT growth of 0.6% from 2018 to 2050, which is only slightly higher than population growth (0.5% per year). Achieving a 30% reduction in VMT by 2050 relative to this projection would require an average *reduction* in VMT per capita of 1.1% per year. The US urban population (including suburban areas) is more than 80% of total population, and that percentage is growing (Census Bureau 2012); we assume that VMT reduction strategies would affect primarily this population. Consequently, urban residents would need to reduce their VMT per capita by about 1.4% per year to achieve the requisite overall reduction.

Our savings estimates do not factor in use of autonomous vehicles. On the one hand, fully autonomous vehicles have the potential to greatly reduce fuel use, in part because shared rides will likely be cheaper when there is no driver to pay. Also, vehicles can be much lighter if collisions can be reduced and are of less concern. On the other hand, investigations of autonomous vehicle scenarios to date point out the various ways their emergence could

²⁵ See <u>www.oregon.gov/ODOT/Programs/Pages/OReGO.aspx.</u>

²⁶ See <u>www.federalregister.gov/documents/2017/01/18/2017-00681/national-performance-management-measures-assessing-performance-of-the-national-highway-system.</u>

²⁷ See <u>www.federalregister.gov/documents/2018/05/31/2018-11652/national-performance-management-measures-assessing-performance-of-the-national-highway-system.</u>

increase the amount of driving (Brown, Gonder, and Repac 2014). Net effects are thus difficult to predict and will depend on policy choices.

Policies

For our policy analysis we model a nationwide VMT fee along with congestion fees. The VMT fee applies to light-duty vehicles and phases in to 3 cents per mile over five years. This would be in addition to the current gas taxes. To estimate the impact on driving, we conservatively assume a constant price elasticity of demand of -0.1, analogous to the 10% rebound effect we also assume for light-duty vehicle use. We believe such a fee would be motivated in large part by infrastructure needs, but we do not model any impacts from associated infrastructure spending. We assume congestion fees collectively would result in a similar reduction in driving and energy use (after any rebound due to the reduced congestion). VMT and congestion fees do raise equity concerns, which might be partially offset by returning a portion of income to low- and moderate-income households.

REDUCTIONS IN FREIGHT TRANSPORT ENERGY USE



Apart from improving the fuel efficiency of individual trucks, highway freight transport can reduce fuel use through a variety of techniques. For example, seamless transitions among highway, rail, water, and air modes will increasingly allow a dynamic, multimodal assignment of goods to the network; this can improve efficiency in multiple ways, including moving loads via the least energy-intensive mode that meets each load's needs. Improved management of supply chains also can reduce and shorten freight shipments. In addition, freight energy use can be reduced by avoiding empty backhauls and increasing the truck load factor, such as through collaborative shipping arrangements. Collaborative shipping could also help increase use of rail, allowing multiple shippers to share a railcar, replacing some use of trucks. Such strategies can draw on growing applications of ICT to mobility. Another strategy is platooning with vehicle-to-vehicle communications. Two-truck platoons with a separation distance of 40–50 feet have been estimated to reduce the trucks' average fuel consumption by 7%. Considering constraints on platooning, this could deliver 4% savings on average in real-world driving (NACFE 2016).

Although freight transportation's evolution will depend largely on the actions of the private sector, the public sector can promote a transition to a less energy-intensive system through actions such as:

- Setting targets for reduced energy use and emissions as program objectives and project selection criteria for freight funding programs and state freight plans
- Helping to standardize information-sharing protocols and equipment to facilitate collaboration and shared use of assets in goods movement
- Promoting innovation through strategic investments in ICT applications to the freight system

- Investing in the development of infrastructure and services that multiple unrelated companies can use
- Conducting further analysis of energy savings, nonenergy benefits, and the costs of alternative future freight scenarios
- Investing in rail, shipping, and intermodal infrastructure to increase the share of less energy-intensive modes.

Savings Opportunity

A 2013 ACEEE survey of literature on the potential to reduce freight energy use found a large range of estimates (Foster and Langer 2013). Studies that took a supply chain perspective and considered changes in factors such as distance traveled, modal mix, and shared usage of vehicles found potential for savings of more than 20% in the medium term (by about 2030), not including vehicle efficiency technology gains. On the basis of this analysis, we assume 25% freight system energy reductions by 2050 (including direct rebound).

Policies

For our policy analysis we again assume a VMT fee and congestion fees for heavy-duty vehicles. Because of their weight, trucks and other heavy vehicles cause major wear and tear on roads and other infrastructure. Thus several countries and the state of Illinois have implemented VMT fees for trucks. While such a fee should vary with weight and other attributes, here we model nationwide fees with a similar cost per gallon of fuel as for light-duty vehicles (9.4 cents per mile for an average truck), along with congestion fees that achieve similar savings. Again, this would be in addition to the current diesel and gas taxes. To estimate the impact on driving, we conservatively assume a constant price elasticity of demand of –0.08, analogous to the 8% rebound effect for heavy-duty vehicle use.

AVIATION EFFICIENCY IMPROVEMENTS



Aviation accounts for nearly 4% of projected 2050 energy use. Furthermore, energy use for aviation is expected to grow more rapidly than all other transportation segments, as well as most non-transportation segments (EIA 2019a).

Energy use per revenue seat mile declined by nearly 50% from 1980 to 2012 (Nadel, Elliott, and Langer 2015). While there are now few empty seats that can still be filled, there remain a variety of other opportunities to further reduce energy use. Airplane manufacturers and airlines are very interested in improving airframe and operational efficiencies, as fuel is a substantial portion of airline operating costs. Manufacturers do substantial R&D, financed in part by military contracts. Operational efficiencies are also a function of air traffic control operation and should be aided by the major upgrade of Federal Aviation Administration systems that is now underway.

In October 2016, the International Civil Aviation Organization (ICAO) reached consensus on capping GHG emissions for international aviation at 2020 levels. Under the plan, 65 nations agreed to a voluntary cap-and-trade program for the 2021–2026 period and a mandatory cap-and-trade program starting in 2027 (Lowy 2016). Many environmental activists were seeking a stronger plan (von Kaenel 2016). In July 2016, the EPA issued an endangerment finding for GHG emissions from aircraft (EPA 2016), a precursor to regulating the emissions; such standards would likely go beyond the ICAO agreement. With the change in administration, such standards have been put on hold, but they could be revived by a future administration. Absent such standards, the European Union in all likelihood will apply its GHG Emissions Trading Scheme to European routes of US airlines. GHG emissions regulations will encourage a variety of actions, particularly efficiency improvements (airframe and operational) such as those we model here and displacement of traditional jet fuel with lower-carbon alternatives such as biofuels and electric engines (the latter primarily on short flights).

Savings Opportunity

Greene and Plotkin (2011) examine opportunities to reduce aviation energy use including improved engines and airframes, operational efficiency, and changes in travel. Their midcase estimate is 32% savings in 2035 and 56% savings in 2050 compared with the *AEO 2010* reference case (extrapolated to 2050). Support for operational savings comes from a recent study in which pilots flying for Virgin Atlantic were reminded and encouraged to save fuel when flying; those pilots reduced fuel use by 7–20% (Gosnell, List, and Metcalfe 2016). Changes in travel could, for example, include businesses using more video meetings and less travel. For our analysis, we use the Greene and Plotkin percentage savings, applied to our *AEO 2019* baseline with linear ramp-up. We apply these savings to all jet fuel use in order to include similar savings in military aviation. We could not find any published estimates on direct rebound in the aviation sector, so absent other data, we assume 5% rebound.

Policies

For our policy analysis we model an airplane fuel efficiency or GHG emissions standard applied to domestic US flights. We assume such a standard would be set at a level to achieve the engine and airframe efficiency estimated by Greene and Plotkin, 25% savings by 2035 and 50% by 2050, but adjusted for our baseline. Since these are equipment standards, we do not include Greene and Plotkin's estimate of operational savings in our policy analysis.

CONSERVATION VOLTAGE REDUCTION AND REDUCTIONS IN LOSSES FROM TRANSMISSION AND DISTRIBUTION SYSTEMS)



In the United States, about 5% of electricity generated is lost during the transmission and distribution (T&D) of power.²⁸ Additional energy is lost from electric wires in homes, buildings, and factories.

At the grid level, losses can be reduced through use of lower-loss wires and transformers and improved control of voltage and other power parameters. Improved transformers, such as those with amorphous steel cores, can reduce losses by about 50–70% relative to current new transformers (York et al. 2017). Also, greater use of distributed generation can reduce grid losses as power never enters the grid or is generated closer to the load (grid losses depend in part on the distance that power is transmitted).

Additional losses in some equipment in homes and buildings can be avoided by improved voltage control on utility circuits, reducing overvoltage through a measure often called conservation voltage reduction (CVR), or volt/VAR optimization if combined with reactive power management. CVR can be cost effectively employed using sensors at the ends of distribution feeders to sense actual voltage and then reducing voltage to the minimum required levels.

Multiple utilities are now implementing CVR (York et al. 2015a), and the number is growing every year. A few utilities, such as Baltimore Gas and Electric, are beginning to implement CVR on a widespread basis (Exelon 2017). A few other utilities, like Hawaiian Electric and Xcel Colorado, are testing grid-edge optimization technologies to make CVR more effective (St. John 2018). Additional testing of volt/VAR grid-edge optimization techniques would be useful to see if the additional 2% savings achieved on a few circuits can be achieved in a widespread manner. Utilities generally make purchase decisions for transformers on a lifecycle cost basis, but with a "band of equivalence" that selects less-efficient transformers with lower first cost even when their life-cycle costs are a little higher. The District of Columbia and Maryland have eliminated this band of equivalence, and as a result sales of amorphous core transformers are significantly higher (York et al. 2017).

More broadly, utilities are gradually improving their T&D systems; losses were more than 7% as recently as 2002, so losses have been reduced by one-fourth (Nadel, Elliott, and Langer 2015). Smart grid efforts and intelligent grid optimization could help continue the

²⁸ See www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

trend. Utility regulators can monitor, support, and ensure implementation of CVR and T&D loss reduction programs.²⁹

Savings Opportunity

T&D losses average about 4% in Germany and about 4.5% in Japan (World Bank 2018). These countries are more compact than the United States, with improved controls and other technologies, as well as greater use of distributed generation. Still, we estimate that the United States can, by 2040, reduce T&D losses to Japan's level, saving 0.5% on the utility side of the meter and not including CVR and volt/VAR where savings are primarily on the customer side of the meter. York et al. (2015a) summarize eight different studies on the savings from CVR, finding average savings of 2.3%. In addition, volt/VAR grid-edge optimization techniques, which on some circuits have demonstrated up to 2% additional CVR savings, are now reaching the market (Moghe et al. 2016). Considering all of these factors, we estimate total T&D savings of 4.5% are possible, with savings achieved over a growing portion of the grid over the 2020–2040 period, reaching 80% of the grid by 2040.

Policies

As these savings are under the control of regulated and publicly owned utilities, we assume that regulators, cities, and cooperative boards could achieve all the savings.

OTHER ENERGY EFFICIENCY OPPORTUNITIES

The 11 measures discussed above do not capture all of the available efficiency opportunities. For example, in our 2016 analysis we also examined savings from behavior-based approaches, combined heat and power (i.e., generating both heat and power from the same high-efficiency system), and improving power plant heat rates. For this paper we do not explicitly include these measures so as to avoid overlap with several related approaches that we do examine, such as smart building measures, industrial process improvements, and building retrofits, and because the savings are often relatively small. But behavior-based savings and combined heat and power (CHP) are in part included in our analysis of smart building technologies and industrial efficiency measures. And while there are still opportunities for heat rate improvements in existing power plants beyond those included in the reference case, with the retirement of many existing power plants in our reference case, the savings are likely modest.

We also do not fully examine some energy end uses such as agriculture, boats, trains, and many types of miscellaneous equipment in the residential and commercial sectors (ranging from elevators to gas pumps). For example, York et al. (2015a) find substantial savings

²⁹ The discussion in this section is based on current conditions. Grid conditions will evolve in various ways due to higher outdoor temperatures, which increase air-conditioning loads and T&D losses; reduced loads from energy efficiency; and increased use of distributed power. These will all interact in complex ways that could yield opportunities to reduce T&D losses that differ from what we model.

opportunities from miscellaneous equipment.³⁰ Some of these opportunities are implicit in smart building measures, whole-house or whole-building retrofits, new-building savings, and other broad opportunities.

Finally, our analysis is based mostly on currently known technologies (although the industrial efficiency and fuel economy sections do include some future technologies). Over the next 30 years, additional energy-saving measures will certainly be identified, adding to the potential savings opportunity. For perspective, remember that 30 years ago LEDs that could emit bright blue light had not yet been invented. That breakthrough came only in 1994, creating the foundation for today's white LEDs.³¹

ENERGY EFFICIENCY RESOURCE STANDARD

We include one policy, an energy efficiency resource standard (EERS), that cuts across multiple economic sectors and efficiency opportunities. Other potential policies, notably carbon pricing via a carbon fee or cap-and-trade program, also could spur large investments in efficiency across multiple sectors of the economy, as well as promoting carbon emissions reductions in other ways. But we limit our analysis to more direct energy efficiency policies. EERS policies also stand out for having many years of success in delivering energy savings.

Most energy efficiency programs in the United States are funded by electricity and natural gas utility ratepayers and run by the utilities or, in some cases, by state agencies or so-called energy efficiency utilities.³² These programs (residential, commercial, and industrial) provide rebates, incentives to businesses and retailers, and technical assistance. Most are under regulatory oversight and are subject to independent evaluation and cost-effectiveness tests.

About half the states require these programs to meet savings targets, sometimes called EERS. A few states, especially in the Northeast, are meeting targets to achieve new electricity savings each year of more than 2% of electricity sales. (As the savings persist over 10 years, on average, in time such savings would accumulate to about 20% of sales.) The leading states have savings goals of more than 3% per year. Natural gas savings have been somewhat lower, as there are fewer programs and natural gas offers fewer opportunities for cost-effective savings (ACEEE 2019). Most municipal utilities and rural electric cooperatives are not currently subject to state EERS, but many run their own efficiency programs.

For our policy analysis we model energy efficiency programs based on a ramp-up to 2% new electricity savings and 1% new natural gas savings each year from 2020 to 2025 (as a percentage of the average policy scenario electric and natural gas use over the previous

³⁰ A few equipment efficiency standards and ENERGY STAR specifications affect miscellaneous energy uses; these uses are also addressed in zero net energy buildings and, to a limited extent, by smart building and building retrofit strategies. Still, we believe other opportunities to reduce miscellaneous uses remain.

³¹ See <u>www.shineretrofits.com/knowledge-base/lighting-learning-center/a-brief-history-of-led-lighting.html</u>.

³² An energy efficiency utility is chartered by a state legislature or state public utility commission to operate energy efficiency programs under the oversight of the utility commission. Examples include Efficiency Vermont, the District of Columbia Sustainable Energy Utility, and the Energy Trust of Oregon.

three years). Because many currently available technologies would be adopted under the codes and standards described earlier, achieving these savings would require bolder and more creative programs to find new savings.

Although states are sometimes allowing large industrial ratepayers to opt out of paying for and using the programs, we assume the same level of savings in each sector and do not reduce the industrial targets. As EVs become commonplace, transportation electricity use increases in our analysis and is included under the policy. We assume that utility programs would achieve the same level of savings in the new transportation electricity use, either through more-efficient electric vehicles or initiatives to decrease driving (we did not assume any further shift to EVs beyond what occurs under the vehicle standards). Reported savings are only what is additional to the current levels of savings (0.7% new electric savings each year and 0.4% gas savings), which we assume are continued indefinitely in the *AEO 2019* baseline. In this analysis, electric savings in all sectors last an average of 10.6 years, and natural gas savings persist 16.1 years, with straight-line decay (Molina 2014).

An EERS policy interacts significantly with other policies. All other electricity and natural gas policies affect the baseline energy use to which the EERS target percentages are applied. In addition, utility-sector efficiency programs often promote and receive credit for market transformation in building retrofits and energy management and in high-efficiency equipment sales, measures that are counted under other policies. Thus our overlap calculation assumes that half of the commercial building benchmarking standard, Home Energy Score standard, and near-term industrial policy savings (but not industrial steps 2 and 3) overlaps with up to half the respective sectoral savings under EERS.

Analysis Results

ENERGY SAVINGS

Our opportunity analysis considers how much energy can be saved each year from 2020 to 2050, and how this compares with an objective of cutting projected US energy use in half by 2050. As noted earlier, our primary business-as-usual baseline is the *AEO 2019*, adjusted for two changes: valuing renewable energy at 3,412 Btus per kWh instead of at the fossil fuel heat rate used by EIA, and assuming faster deployment of renewables such that in 2050 the electric generation mix includes 43% renewables and 5% coal. With this modified baseline, reference case energy use in 2050 is 96.5 quads.

For our energy efficiency case, which includes all 11 strategies included in our opportunity analysis, we find that, taken together, the energy efficiency measures we examined would reduce 2050 energy use by 49% relative to our adjusted baseline, bringing 2050 energy use down to 49 quads and showing a path to achieve the 50% energy savings goal. Note that this result does not include savings from measures that are already included in the *AEO 2019* (including large savings under recent vehicle and appliance standards and from utility efficiency programs). Energy use and savings in our efficiency case relative to the various baselines is presented in figure 2. We have grouped some related policies together to make the figure easier to read. All of the various measures contribute significant savings, with no measure or measures dominant.



Figure 2. Energy use in the reference and efficiency cases

The combined savings are dramatic, but they would require sustained transformation of almost all buildings, equipment, industrial plants, and vehicles as well as effective operational energy management of all of them. Although some other countries are ahead of us, none has achieved efficiency at this scale.

EMISSIONS REDUCTIONS

We also looked at energy-related carbon dioxide (CO₂) emissions in the reference and efficiency cases.³³ Our primary reference case is again with an altered generation mix, which reduces 2050 base-case emissions from 5,019 million metric tons (MMT) to 4,353 MMT, a 13% reduction relative to the *AEO* reference case. Efficiency-case emissions are based on energy savings for each fuel per our analysis and average emissions rates for each as estimated by EIA. Details of the assumptions and analysis are provided in Appendix A. In the efficiency case, 2050 CO₂ emissions are reduced by 57% relative to our 2050 reference case, more than putting carbon emissions on a 50% reduction path (see figure 3). Emissions reductions on a percentage basis are greater than energy savings primarily due to the influence of electrification (EVs and heat pumps), which shifts some energy use and emissions from fossil fuels to an increasingly decarbonized electric grid. We discuss this issue further below.

We can also make comparisons with overall US GHG abatement goals. This requires inclusion of emissions of other GHGs. EIA does not project emissions of other GHGs or

³³ Energy-related carbon dioxide emissions are estimated in the *AEO* and in 2017 accounted for about 80% of total US GHG emissions on a carbon dioxide equivalent basis. Other major emissions are methane (10% of the total), nitrous oxide (6%), fluorinated gases (3%), and other carbon dioxide emissions (3%). (EPA 2019). Land sinks absorbed 11% of the emissions.

nonenergy carbon dioxide emissions (e.g., from industrial processes such as Portland cement production). But those emissions have been slowly declining since 1998 (EPA 2019), and projections out to 2030 suggest they will remain relatively flat (DOS 2016; Larsen et al. 2018). Carbon sinks have also been relatively flat, though projections range widely. For this analysis we assume net emissions not included in the *AEO* will remain at 2017 levels through 2050, at 596 MMT per year. We also exclude the reduction in fugitive emissions of methane due to reduced natural gas and coal use in our efficiency scenario. With these assumptions, in our efficiency case total US GHG emissions are reduced by 49% by 2050 relative to the reference case projection. This reduction is two-thirds of the total GHG abatement needed from the reference case projection to reach a goal of 80% reduction in 2050 compared with 2005 levels (i.e., reaching 1,320 MMT emissions).³⁴



Figure 3. Energy-related carbon dioxide emissions in the reference and efficiency cases

THE ROLE OF ELECTRIFICATION

Our analysis includes electrification in several sectors. The largest amount of electrification is in the transportation sector: in our opportunity case, by 2050 electric vehicles ramp up to more than 75% of the passenger vehicle stock and 50% of the medium- and heavy-duty stock. The second-largest amount of electrification is in the industrial sector, for which we estimate about 25% of our GHG emissions reductions are from electrification. The buildings sector follows closely behind, including electrification of space and water heating in existing homes and buildings (as discussed in the section above on electrification of existing buildings) as well as new zero energy homes and buildings, which we assume will generally

³⁴ Even if other net GHG emissions double, efficiency would still cut total 2050 GHG emissions by 44%.
use heat pumps. Overall, we estimate that by 2050, electrification will reduce carbon dioxide emissions by about 850 MMT, which is about 35% of the total 2050 emissions reductions we estimate. Of these emissions reductions from electrification, 72% are in the transportation sector, 14% in the industrial sector, and 14% in the buildings sector.³⁵ We also looked at other estimates of electrification impacts by sector, and all of the studies we examined estimate that more than 50% of the savings are in the transportation sector; estimates for the buildings and industry sectors vary from study to study, but most find substantial opportunities in both (Gowrishankar and Levin 2017; EPRI 2018; Mai et al. 2018; Billimoria et al. 2018).

TRANSLATING OUR RESULTS INTO ENERGY PRODUCTIVITY TERMS

This analysis focuses on reducing energy use. Other analyses, such as ones by the Alliance to Save Energy and the DOE, have focused on a related metric, energy productivity, with an explicit goal of doubling energy productivity by 2030 relative to 2010 (Rhodium Group 2013; DOE 2015). Energy productivity is a measure of the average gross domestic product (GDP) per unit of energy consumption. For example, the *AEO 2019* predicts an energy productivity for 2019 of \$187 billion per quad of energy use.³⁶ In our reference case for 2050, this improves by 77%, to \$332 billion per quad. In our efficiency case for 2030, energy productivity increases to \$280 billion per quad, more than double the 2010 base of \$134 billion per quad used by DOE (2015). By 2050, energy productivity is increased by a factor of 3.45 relative to 2019 levels, rising to \$647 billion per quad.³⁷ Energy productivity more than triples while energy use declines only 49% because GDP is expected to grow substantially in the coming decades (up 77% in inflation-adjusted dollars, according to the *AEO 2019*). Energy productivity measures give credit to this GDP growth, while our 50% savings target is an absolute reduction that we seek to achieve even as GDP grows substantially.

SAVINGS BY SECTOR

Energy and emissions reductions can be found in each of the major end-use sectors — residential, commercial, industrial, transportation — as well as the power sector. The four end-use sectors each account for between 19% and 32% of the total energy savings, with savings a little higher in the transportation and industrial sectors. Emissions reductions from the transportation sector are nearly half the total reductions due to both efficiency

³⁵ In the buildings sector, as discussed above for existing buildings, we assume that aggressive building shell and other measures reduce baseline energy use substantially, lowering the amount of fuel use that is electrified and the estimated emissions reductions. In the transportation sector, we compare electric vehicles with baseline gasoline or diesel vehicles before applying efficiency measures, so efficiency does not reduce the estimated electrification impacts. For the industrial sector, we estimate the electrification impact as a portion of the efficiency impact.

³⁶ The productivity figures in this paragraph are with renewable electricity valued at 3,412 Btus/kWh and expressed in 2009 dollars.

³⁷ This calculation assumes that GDP will be the same in the reference and efficiency cases. In fact, prior ACEEE analyses (e.g., Hayes et al. 2014) have shown that large efficiency improvements can modestly increase GDP, a factor that would raise energy productivity to a value slightly higher than what we show here.

gains in carbon-intensive oil-based fuels and switching to substantially cleaner electricity. The industrial sector also has significant emissions reductions due to extensive use of fossil fuels in the sector. Emissions reductions are smaller in the residential and commercial sectors, as much of the savings are in electricity (with a much cleaner grid by 2050) and natural gas (the cleanest of the fossil fuels). These trends are illustrated in figure 4.³⁸



Figure 4. Allocation of energy savings (left) and emissions reductions (right) among sectors

SAVINGS BY MEASURE

Each of the 11 efficiency opportunities we examined contributes to putting us on the path to a 50% reduction in energy use. The proportion of total 2050 energy and emissions savings by measure (with some measures subdivided into constituent parts) is illustrated in figures 5 and 6.

The largest energy savings come from industrial efficiency measures, which combined contribute about 12% of total energy use reduction in 2050. Other measures that account for at least 5% energy savings in 2050 are zero energy homes and buildings (6% combined), efficient passenger and commercial vehicles (9% combined), appliances and equipment (6%), and improvements to existing buildings (7% including smart homes/buildings and residential/commercial retrofits). Improving the movement of vehicles and freight accounts for nearly 5% of the energy savings, aviation improvements more than 2%, and existing building electrification and transmission/distribution system improvements almost 1% each.³⁹ It should be noted that the savings from building electrification are small in part because we first apply efficiency measures to these buildings, reducing loads, before calculating the energy savings from electrification.

³⁸ Note that the Power wedge only includes the grid opportunity. End-use electricity savings are large but are distributed in the sector wedges.

³⁹ Note the percentages in the pie graphs are the portion of the total savings, but the percentages in the text are of total energy use or emissions, and hence differ.



Figure 5. Allocation of energy savings among measures

For 2050 emissions savings, the results are broadly similar, with several major exceptions. Efficient vehicles (passenger and commercial) result in about 17% of all emissions reductions, much more than their 9% energy savings. Likewise, the percentage of emissions reductions due to building electrification is nearly double its percentage of energy savings. In both cases, as noted earlier, the larger proportions of emissions reductions are due to the replacement of higher-emission fossil fuels with lower-emission electricity. Likewise, due to the high GHG intensity of jet fuel, aviation accounts for 4% of all emissions reductions.



Figure 6. Allocation of CO₂ emissions reductions among measures

SAVINGS RELATIVE TO AEO 2011 BASELINE

This paper examines 2050 energy use based on the *AEO 2019*. As noted in the Introduction, an earlier ACEEE analysis found opportunities to reduce 2050 US energy use by 40–60% (Laitner et al. 2012). This was relative to a baseline extrapolated from the *AEO 2011*. Based on this analysis, ACEEE established a goal of cutting projected 2050 US energy use in half. Our updated analysis estimates that 2050 energy use can be reduced to less than 50 quads, which would exceed our goal based on the *AEO 2011*. Progress over the past eight years plus our updated potential estimate show that the 2011 goal is within reach.⁴⁰

POLICY ANALYSIS SAVINGS

Our policy analysis finds that 91% of the primary energy savings opportunity in 2050 could be achieved through the set of 11 policies if fully implemented. Efficiency measures spurred by the policies would reduce US energy consumption in that year to 55 quads, a 44% reduction, as shown in figure 7. The energy saved would be worth a total of \$704 billion at the *AEO 2019*'s projected prices; although we did not estimate the largely private investment that would be required to achieve the savings, we believe it would be much lower. The policies also could achieve 91% of the 2050 carbon reduction opportunity, 2.2 billion metric tons of CO₂. As shown in figure 8, that is 51% of the reference case projected emissions (as with the opportunities analysis, a higher percentage of carbon savings than of energy savings).

⁴⁰ Extrapolating from the *AEO 2011*, estimated energy use for 2050 is 124 quads if renewable energy use is counted at the fossil fuel heat rate. If we count renewable electricity at 3,412 Btus per kWh, the 2050 estimate derived from the *AEO 2011* drops to 120 quads. Thus a 50% reduction would target about 60 quads of energy savings by 2050. Our new analysis has a reference case 2050 energy use of 97 quads (valuing renewable electricity at 3,412 Btu per kWh), a drop of more than 20 quads relative to the adjusted earlier projection, indicating significant progress toward the 60-quad goal. We did not do a detailed comparison between the *AEO 2011* and *AEO 2019*, but significant efficiency improvements occurred between 2011 and 2015 (see Nadel, Elliott, and Langer 2015). In addition, with renewable energy valued at 3,412 Btu per kWh, some of the savings are due to increased renewable energy use in 2050. The *AEO 2011* projected 11% of electricity would come from noncombustible renewable energy when extrapolated to 2050. As discussed in the Methodology section, the *AEO 2019* projects 29%, and our analysis estimates 43%.



Figure 7. Energy use in the reference and policy cases



Figure 8. Energy-related carbon dioxide emissions in the reference and policy cases

Similar to the opportunities analysis, the projected savings are large and are based on an aggressive and wide-ranging set of policies that would affect nearly every home, business, and vehicle. The policies would need to leverage trillions of dollars in private investment, though they would yield still larger savings. Even Massachusetts and California have not adopted some of these policies, though many states and cities have established climate goals with even greater levels of abatement. The federal government today is certainly far from this level of ambition. That said, we have modeled a limited set of policies – adding others could achieve even more of the savings opportunity we identify.

The savings vary by energy source. In 2050 the set of policies would save 49% of natural gas use, 37% of oil use, and (even after the substantial shift to electric vehicles and equipment) 28% of electricity use (the vast majority of coal use is for electric power and is almost phased out in the baseline). These savings do not include the upstream impacts from reduced oil and natural gas use.

The savings are somewhat larger than those estimated in our earlier policy analysis (Ungar 2018) if one excludes the savings from current policies from that analysis. The 2018 long-term analysis included a stronger EERS and more stringent appliance standards. However the present analysis includes more transformational vehicle standards (including electrification) and much more industrial savings. It also adds requirements for electrification of existing homes and buildings as well as improvements to the electric grid, among smaller changes.

SAVINGS BY POLICY

All of the policies we examined make significant contributions to energy savings and emissions reductions. The proportion of total 2050 energy and emissions savings by policy is illustrated in figures 9 and 10 (in these figures, we did not remove overlap of savings to allow better comparison of the individual policies). The largest savings are from industrial policies, vehicle standards, and appliance and equipment standards, saving 11, 8, and 5 quads respectively in 2050. These measures stand out due to the large savings that are possible in new processes, vehicles, and equipment and, in the latter two cases, due to the effectiveness of standards. For each of these we assumed the full corresponding efficiency opportunities could be achieved through the respective policies, though the industrial policies will need to be better defined and tested.







Figure 10. Allocation of CO₂ savings among policies

Building energy codes for new construction and standards for existing commercial buildings and homes contributed about 5 quads each in 2050, with commercial building savings much larger than residential in both cases. The codes that we modeled (with more rapid improvements than we have seen historically) would achieve about four-fifths of the ZEB savings. The existing commercial building standard is not exactly equivalent to the smart buildings and building retrofit opportunities but would achieve a similar level of savings. The home sale and rental requirement achieves about a third of the corresponding residential savings in part because we assumed the requirements would apply only when home occupants change. We should note that standards for existing homes and commercial buildings are relatively new and untested.

Strengthened efficiency programs under energy efficiency resource standards also could achieve 5 quads of savings in every economic sector, with more rapid growth than the buildings policies, but we believe the measures taken under EERS would have substantial overlap with the above policies, and thus would facilitate them as much as add to them.

The other transportation policies make somewhat smaller contributions. The airplane efficiency standard we model would achieve almost 90% of the opportunity (the rest involves operational and behavioral changes). The vehicle miles traveled fee and congestion fees would achieve about 30% of the corresponding savings for light-duty vehicles and 25% of the savings for heavy-duty vehicles (the difference is mostly due to lower assumed elasticity of demand). We do not have extensive experience with any of these policies, and other policies also would be needed to achieve significant additional transportation reductions over the three decades in this analysis.

Conclusions

Our analysis finds that the 11 efficiency opportunities we examine, if pursued aggressively, would reduce 2050 energy use by 49%, showing a path for the United States to reduce 2050 energy use by 50% relative to currently predicted levels. These measures can reduce US energy-related carbon dioxide emissions by 57% in 2050 relative to base-case estimates. When other GHGs are included, energy efficiency reduces total 2050 GHG emissions by about half. Our policy analysis identifies a set of policies that if fully implemented could achieve about 90% of these savings. Of course, technologies and demographics will surely surprise us in the decades covered by the analysis; the specific numbers are an illustrative scenario.

In any case, this is not a prediction but a challenge. Achieving these energy savings will require an unprecedented expansion of energy efficiency policies and investments, affecting how we work, live, shop, and move around, including

- Rapid upgrades to vehicle standards, building energy codes, equipment efficiency standards, ENERGY STAR specifications, and energy efficiency resource standards
- Substantial improvements to existing factories, homes, commercial buildings, and the electric grid, and better management of energy use in all of them
- Efforts throughout the country to provide more mobility options and more-efficient freight and aviation systems
- Development and adoption of new industrial processes and systems
- A switch to electric vehicles, equipment, and industrial processes when these need to be replaced (along with a more efficient and cleaner power sector).

While all of these opportunities are important, those with the largest savings, as shown in figure 5 and 6, are industrial efficiency improvements, ZNE buildings and homes, light- and

heavy-duty vehicle fuel economy and electrification, appliance and equipment efficiency efforts, and upgrades to existing homes and buildings.

A comparison of our opportunity and policy pathways shows that the gap between opportunity and policy is largest for transportation system improvements (VMT reduction and freight optimization) and improvements to existing buildings. Although we assume full savings from industrial efficiency policies, those policies are not well defined. More attention is needed to develop policies that will spur energy savings and emissions reductions in these areas. Fortunately, transportation systems and existing buildings are two areas in which cities and regions that have adopted climate goals can experiment with bold policies.

To achieve the savings, we must also continue to invest in research, development, and demonstration (RD&D) to identify and validate new efficiency measures; these measures will provide additional savings opportunities that we can only imagine today and that will complement the measures we examine. RD&D will also be essential for developing and testing many of the emerging industrial and transportation technologies we include and for continuing to drive costs down.

While we expect vast consumer savings, even our current efficiency measures were not implemented solely to save money. Through these steps, we can not only reduce energy use but also improve productivity, the economy, personal comfort, air quality, and public health. And we can slash GHG emissions, getting roughly halfway to our long-term energy and climate goals.

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Appendix A. Methodology Details

ANALYTICAL APPROACH

As described in the main text, we conducted two analyses, one on efficiency opportunities and a second on efficiency policies. For each analysis our approach started with a baseline case based on the reference case in the *Annual Energy Outlook 2019* (EIA 2019a). We compared this with two cases we prepared, one estimating the combined energy savings from a set of energy efficiency measures (opportunity analysis) and the other estimating savings from a set of energy efficiency policies (policy analysis). We mostly reported the impact on primary energy consumption (meaning that "upstream" energy consumed in power generation, mining, and drilling is included) and on carbon dioxide emissions.

Reference Case

We used the *Annual Energy Outlook 2019* (*AEO 2019*) as the foundation for our reference case. The *AEO* provides a detailed forecast of US energy use out to 2050. We used the *AEO* because it is probably the most widely used forecast of US energy use and supply and is publicly available, easy to use, and well documented. While we generally used *AEO 2019*, we made two adjustments to its reference case to produce a revised reference case for our analysis. These adjustments involved 1) the assumed heat rate, and 2) the assumed penetration of electricity generation from renewable energy.

To derive primary energy use from renewable electricity, the *AEO 2019* calculates how much energy was used to generate electric power from most renewable sources at the average heat rate for fossil-fuel power plants (about 9,200 Btus per kWh of electricity in 2019), i.e., as equivalent to the amount of fossil fuel they might have displaced. While this is a minor factor when renewable generation is low, the impact of this assumption will become substantial as renewable energy generation increases over the 2019–2050 period. Therefore we adjusted the *AEO 2019* to value power from noncombustible renewable energy⁴¹ at the heat content of the electricity generated, which is 3,412 Btus per kWh of electricity.⁴² This follows the current policy of the Energy Efficiency and Renewable Energy Office at the US Department of Energy (Donohoo-Vallett 2016). Our approach also is similar to that of the International Energy Agency (IEA 2019).

After this accounting adjustment, the overall electricity heat rate in the *AEO 2019* improves nearly 1.5% per year from 2014 to 2023 but then slows down to about 0.5% per year over the 2024–2050 period. The primary reason is that *AEO 2019* assumes that use of renewable energy grows less than 2% per year on average from 2024 to 2050. We believe these assumptions are very conservative, and therefore our analysis assumes about 3% annual growth in renewable power generation in our reference case, with a corresponding

⁴¹ Hydropower, wind, solar photovoltaic and thermal, and geothermal. But note that *AEO* does not count customer renewables, such as rooftop solar, at all in primary energy use.

⁴² Btu stands for *British thermal unit*, a common metric for energy consumption. kWh stands for *kilowatt-hours*, a common metric for electricity use. There are 3,412 Btus in a kWh.

reduction in coal use.⁴³ These changes, plus improvements in generating plants in the *AEO* 2019 reference case, result in a 0.95% per year annual improvement in heat rate from 2024 to 2050. The impact of these changes on generation mix and primary energy use in the reference case is shown in table A1. These changes are more conservative than the 2050 coal generation share (2%) and renewable generation share (55%) projected in the *New Energy Outlook* published by Bloomberg New Energy Finance (Gearino 2019; BNEF 2018).⁴⁴

	:	2019	:	2050
	AEO	Modified	AEO	Modified
Natural gas	3	4%	39%	39%
Coal	2	8%	19%	5%
Renewables	1	.8%	28%	43%
Nuclear	2	0%	14%	14%
Overall heat rate	9,978	9,100	8,657	6,526
Primary energy (quads)	37.7	36.0	40.7	31.8

Table A1. Electric generation mix in *AEO 2019* reference case and our modified reference case

We also considered, but did not adjust for, energy efficiency already included in the *AEO* 2019. The *AEO* includes the impacts of established efficiency policies on future energy use, including established vehicle and appliance efficiency standards and building codes, as well as the continuation of energy efficiency programs at historic levels and projections of market-based adoption of efficiency technologies. We could have taken some of these savings out of our reference case and then included these savings in our analysis. Instead we focused on new strategies and policies rather than trying to back-out the impact of existing strategies and policies.⁴⁵

Rebound and Upstream Energy Savings

Our analysis also includes consideration of direct rebound effects. Direct rebound is the impact of purchasing an efficient product on the purchaser's use of that product. For example, homeowners with an efficient air conditioner might run that air conditioner longer than they would run a less efficient model. For most measures, we reduced energy savings

⁴³ Specifically, we gradually reduced coal use to 5% of the US generation mix in 2050 (rather than 19% in the *AEO*), assigning the change in coal share to renewable energy.

⁴⁴ Our modified reference case on coal use is also more conservative than a recent estimate by Moody's Investor's Service (2019) that "likely [coal] closures, such as power plants more than 50 years old, would reduce coal to as little as 11% of total U.S. power generation in 2030." Our modified reference case is that coal will be 19% of the 2030 generation mix.

⁴⁵ In our 2018 study (Ungar 2018), we did include savings from recent vehicle standards, appliance standards, building codes, and ratepayer-funded efficiency programs, with somewhat different assumptions and methodology, and estimated those savings in 2050 to be 20% of the *AEO 2018* projected energy use for that year.

to account for direct rebound, usually by 10% (homes, light-duty vehicles) or 5% (commercial buildings, industry, and aviation). These figures are for the United States and are generally based on a recent paper reviewing many previous studies on the rebound effect (Nadel 2016c). We did not include indirect rebound, which reflects broader impacts, such as the impact of re-spending money saved on energy bills; some of this re-spending might increase energy use.⁴⁶

We also included upstream energy impacts, i.e., energy used to drill, produce, refine, or transport the fuel or electricity delivered to the end user, in the analysis for primary energy and GHG savings (they were not included where we reported results for specific fuels). Losses from electric generation as well as transmission and distribution were included in the heat rate discussion above. For oil products we added to our savings estimates a proportional amount of *AEO 2019*'s estimate of refining energy use and carbon emissions, and we added 7% to energy use and emissions to account for transport (Delucchi 2003, table 51B). For natural gas we added a proportional amount of *AEO 2019*.

Emissions Abatement

Reducing direct fuel use and electricity use lowers carbon dioxide emissions from burning fossil fuels. (It also cuts emissions of other pollutants, but that was outside the scope of our analysis.) We typically assumed that energy savings would reduce energy sources proportionately, except for electrification. For savings of natural gas, oil products, and coal, we used carbon intensities from EIA (EIA 2016a). We assumed that electricity savings would reduce sales from the grid and that power sector sources would be reduced proportionately based on our modified reference case for a given year. To estimate emissions reductions, we assumed average emissions factors for natural gas and coal plants each year drawn from *AEO 2019* but used the revised generation mix from our reference case. Although marginal electric emissions can be quite different from average emissions, we cannot predict that difference for deep reductions decades in the future.

OPPORTUNITY AND POLICY CASES

Energy Efficiency Opportunity Case

To assess the potential impact of energy efficiency on economy-wide energy use in the United States, we looked at 11 packages of energy efficiency technologies, practices, and programs targeted at specific end-use sectors. We estimated the energy savings of each package based on current research findings and ACEEE expert judgment. For most of the packages, we looked at the base energy use in the 2020–2050 period that would be affected (as projected in the *AEO 2019*), how much each package could reduce energy use (as a percentage), and what portion of this use could be affected (also as a percentage). When estimating these percentages, we considered what was likely to be cost effective to end users and society, but for this project we did not do a specific economic analysis. For some

⁴⁶ We did not adjust for indirect rebound because its effect is much harder to prove, and economists have widely different opinions of its potential size. Nadel (2016b) finds that indirect rebound averages about 10%, so adjusting for indirect rebound would reduce our energy savings estimates by about 10% and GHG abatement by a similar percentage.

measures, the percentage savings applies to only a portion of use. For others, the percentage reduction is an average reduction that applies to 100% of the use (recognizing that some users will save more than the average, and some will save less).

Some overlap exists between savings from the measures, so we made a variety of adjustments to eliminate overlap. In particular, for many of the measures we reduced the base-case energy use to account for the impact of savings from other measures. For transportation system measures and one measure related to the transmission and distribution of electricity, we increased base-case electricity use to account for measures, such as electric vehicles, that add to electric loads.

Policy Case

We also assessed how much of the savings potential that we found in the opportunity analysis could be achieved under a set of 11 government policies applied nationwide (beyond the current policies included in the reference case). We estimated the impacts from the set of policies separately from the opportunity analysis, but in some cases we assumed that a policy could achieve the full savings estimated for the associated opportunity. Some of the policies extend across multiple opportunities, and one across multiple economic sectors.

To estimate savings from the policies, we mostly used a methodology similar to the one we used for the opportunities, in order to keep the calculations comparable. As we did for the opportunity case, we adjusted baselines to remove overlap in the savings from different policies (e.g., improving a building shell achieves some of the savings one would get from better heating and cooling equipment). But for policies there also was some overlap in the measures they spur (e.g., an energy efficiency resource standard and a building efficiency requirement may motivate the same equipment upgrade). In these cases, we subtracted some savings from each policy to account for this overlap.

Details of and assumptions for each opportunity and policy are described in the main text and in Appendixes B and C.

Appendix B. Opportunity Analysis Details

Table B1. Energy savings and \mbox{CO}_2 emissions reductions by measure and year

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Primary energy savings																
Appliances and equipment	0.06	0.13	0.22	0.35	0.57	0.78	0.96	1.14	1.31	1.52	1.76	2.07	2.34	2.62	2.93	3.22
Zero energy new comm. buildings	0.01	0.02	0.04	0.06	0.09	0.12	0.16	0.21	0.26	0.31	0.37	0.46	0.56	0.67	0.79	0.93
Zero energy new homes	0.00	0.01	0.02	0.04	0.05	0.07	0.10	0.12	0.15	0.18	0.21	0.26	0.32	0.38	0.45	0.53
Smart buildings	0.10	0.20	0.30	0.39	0.49	0.58	0.66	0.75	0.84	0.92	1.00	1.08	1.15	1.22	1.29	1.35
Smart homes	0.08	0.16	0.24	0.31	0.38	0.45	0.52	0.58	0.64	0.70	0.76	0.81	0.87	0.92	0.96	1.00
Building retrofits	0.13	0.25	0.36	0.48	0.58	0.69	0.79	0.89	0.98	1.07	1.16	1.24	1.32	1.39	1.46	1.52
Home retrofits	0.11	0.22	0.32	0.41	0.50	0.59	0.67	0.75	0.83	0.90	0.97	1.04	1.10	1.16	1.21	1.25
Existing building electrification	0.01	0.03	0.04	0.06	0.07	0.09	0.10	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.19
Existing home electrification	0.02	0.05	0.09	0.12	0.15	0.18	0.21	0.25	0.28	0.31	0.33	0.36	0.38	0.41	0.43	0.45
Industrial current measures	0.17	0.35	0.53	0.71	0.90	1.09	1.28	1.47	1.67	1.86	2.05	2.25	2.44	2.63	2.83	3.03
Industrial emerging technologies	0.00	0.00	0.00	0.00	0.00	0.13	0.26	0.39	0.52	0.64	0.77	0.90	1.02	1.15	1.27	1.55
Car and light truck efficiency	0.01	0.03	0.05	0.09	0.13	0.18	0.25	0.35	0.48	0.62	0.80	0.98	1.18	1.39	1.63	1.86
Truck and bus efficiency	0.01	0.03	0.06	0.08	0.11	0.13	0.17	0.20	0.25	0.33	0.42	0.52	0.64	0.76	0.90	1.05
Reducing driving	0.00	0.18	0.37	0.54	0.71	0.87	1.01	1.14	1.26	1.37	1.47	1.56	1.65	1.72	1.79	1.85
Improving freight movement	0.00	0.10	0.20	0.31	0.41	0.50	0.60	0.69	0.79	0.87	0.95	1.03	1.11	1.18	1.25	1.32
Aviation efficiency	0.06	0.12	0.17	0.23	0.29	0.35	0.42	0.48	0.55	0.61	0.68	0.75	0.82	0.89	0.97	1.04
Electric distribution savings	0.05	0.09	0.14	0.20	0.26	0.33	0.37	0.42	0.47	0.51	0.55	0.59	0.63	0.66	0.70	0.73
Total	0.82	1.98	3.15	4.37	5.69	7.13	8.53	9.94	11.40	12.88	14.41	16.06	17.69	19.33	21.04	22.88
Baseline energy use (adjusted)	96.53	96.11	95.85	95.35	95.03	94.64	94.43	94.26	94.27	93.96	93.64	93.57	93.49	93.31	93.24	93.20
Energy savings as a % of baseline	0.9%	2.1%	3.3%	4.6%	6.0%	7.5%	9.0%	10.5%	12.1%	13.7%	15.4%	17.2%	18.9%	20.7%	22.6%	24.5%
CO ₂ emissions reductions																
Appliances and equipment	3	6	11	17	28	38	46	55	63	72	83	96	109	120	133	145
Zero energy new comm. buildings	0	1	2	3	4	6	8	10	12	15	17	22	27	32	39	46
Zero energy new homes	0	1	1	2	3	4	5	6	7	8	10	12	15	18	22	26
Smart buildings	5	10	15	20	24	29	33	37	41	45	48	51	55	58	60	63
Smart homes	4	8	12	16	19	22	25	28	31	34	36	38	41	43	44	46
Building retrofits	6	12	18	24	29	34	39	44	48	52	56	59	63	65	68	7(
Home retrofits	6	11	16	20	25	29	33	37	40	43	46	49	52	54	56	57
Existing building electrification	1	3	3	5	6	7	9	10	11	12	13	14	15	15	16	17
Existing home electrification	2	5	7	10	13	15	18	21	23	26	28	30	31	33	35	3(
Industrial current measures	8	16	24	32	40	48	56	65	73	81	88	97	105	112	120	128
Industrial emerging technologies	0	0	0	0	0	6	11	17	23	28	33	39	44	49	54	6
Car and light truck efficiency	1	3	5	8	12	17	23	32	43	55	70	86	102	121	141	16
Truck and bus efficiency	2	3	6	8	11	13	17	20	25	32	39	49	58	69	81	93
Reducing driving	0	12	25	36	47	58	67	76	83	90	97	102	107	112	115	118
Improving freight movement	0	7	14	21	28	34	41	47	53	59	64	69	74	78	83	8
Aviation efficiency	4	8	12	16	20	24	28	32	37	41	45	50	55	59	64	69
Electric distribution savings	2	4	7	10	12	16	18	20	22	23	25	26	28	29	30	3
Total	44	109	176	246	320	399	477	554	634	715	798	888	979	1.068	1,161	1.258
Baseline energy CO ₂ emissions	5,116	5,050	5,038	4,991	4,939	4,902	4,872	4,835	4,808	4,758	4,710	4,683	4,664	4,628	4,601	4,570
Emissions reductions (%)	0.9%	2.2%	3.5%	4,991	6.5%	8.1%	9.8%	11.5%	13.2%	15.0%	16.9%	19.0%	21.0%	23.1%	25.2%	27.5%
LIIISSIOIIS IEUULIOIIS (70)	0.9%	2.2%	5.5%	4.9%	0.5%	0.1%	9.0%	11.5%	13.2%	10.0%	10.9%	19.0%	21.0%	23.1%	23.2%	27.5%

Appliances and equipment 3.47 3.69 3.88 4.08 4.29 4.84 4.70 4.84 5.16 5.28 5.40 5.49 5.40 5.49 5.40 5		2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	% of total
Zero energy new comm. buildings 1.07 1.23 1.40 1.58 1.77 1.97 2.16 2.34 2.53 2.72 2.90 3.08 3.26 3.44 3.62 3.77 Zero energy new homes 0.62 0.71 0.81 0.92 1.04 1.47 1.52 1.57 1.61 1.66 1.07 1.74 1.82 1.86 1.90 1.94 1.90 2.00 2.02 2.10	Primary energy savings																
Zero energy new homes 0.62 0.71 0.81 0.92 1.02 1.04 1.25 1.63 1.58 1.69 1.79 1.90 2.00 2.10 2.21 Smart holidings 1.41 1.47 1.52 1.57 1.61 1.66 1.70 1.74 1.78 1.58 1.69 1.79 1.90 2.00 2.21 Smart homes 1.00 1.04 1.06 1.07 1.07 1.81 1.84 1.88 1.91 1.41 1.15 1.16 1.16 1.71 1.18 1.84 1.88 1.91 1.94 1.90 2.00 2.03 2.06 2.09 2.17 1.81 1.84 1.88 1.91 1.94 1.90 2.00 2.03 2.02 2.02 2.02 2.02 2.02 0.21 0.	Appliances and equipment	3.47	3.69	3.88	4.08	4.29	4.48	4.67	4.84	5.01	5.16	5.28	5.40	5.49	5.56	5.64	5.8%
Smart buildings 1.41 1.47 1.52 1.57 1.61 1.66 1.70 1.78 1.82 1.86 1.90 1.94 1.98 2.02 2.13 Smart homes 1.00 1.04 1.06 1.07 1.09 1.10 1.11 1.12 1.14 1.15 1.15 1.16 1.17 1.18 1.09 2.02 0.20 0.20 0.20 0.20 0.21 <t< td=""><td>Zero energy new comm. buildings</td><td>1.07</td><td>1.23</td><td>1.40</td><td>1.58</td><td>1.77</td><td>1.97</td><td>2.16</td><td>2.34</td><td>2.53</td><td>2.72</td><td>2.90</td><td>3.08</td><td>3.26</td><td>3.44</td><td>3.62</td><td>3.7%</td></t<>	Zero energy new comm. buildings	1.07	1.23	1.40	1.58	1.77	1.97	2.16	2.34	2.53	2.72	2.90	3.08	3.26	3.44	3.62	3.7%
Smart home 1.02 1.04 1.06 1.07 1.09 1.10 1.11 1.12 1.14 1.15 1.15 1.16 1.17 1.18 1.19 1.27 1.81 1.84 1.88 1.91 1.94 1.97 2.00 2.03 2.02 2.03 3.03 3.00 0.01 4.36 4.33 4.34 4.57 4.37 3.44 4.75 1.56 1.66 1.07 1.01 1.01 1.01 1.01 1.01 1.01 1.01 1.01 1.01 1.01 1.01	Zero energy new homes	0.62	0.71	0.81	0.92	1.03	1.14	1.25	1.36	1.47	1.58	1.69	1.79	1.90	2.00	2.10	2.2%
Building retrofits 1.58 1.68 1.68 1.73 1.77 1.81 1.84 1.85 1.91 1.94 1.97 2.00 2.03 2.06 2.09 2.23 home retrofits 0.20 0.20 0.20 0.21 0.23 2.25 2.83 2.80 1.43 1.51 1.51 1.51 1.51 1.51 1.56 1.66 1.61 1.61 1.61 1.61 1.61 1.61 1.61 1.61 1.61	Smart buildings	1.41	1.47	1.52	1.57	1.61	1.66	1.70	1.74	1.78	1.82	1.86	1.90	1.94	1.98	2.02	2.1%
Home retrofits 1.30 1.30 1.39 1.43 1.47 1.50 1.53 1.59 1.62 1.64 1.66 1.69 1.71 1.73 1.83 Existing building electrification 0.70 0.20 0.20 0.21 0.20 0.21 2.35 2.50 0.63 0.43 4.43 4.49 0.23 2.46 2.49 2.46 2.48 2.49 2.48 2.48 2.49 2.48 2.48 2.48 2.48 2.48 2.48 2.48 2.48 2.49 2.48 2.48 2.48 <td>Smart homes</td> <td>1.02</td> <td>1.04</td> <td>1.06</td> <td>1.07</td> <td>1.09</td> <td>1.10</td> <td>1.11</td> <td>1.12</td> <td>1.14</td> <td>1.15</td> <td>1.15</td> <td>1.16</td> <td>1.17</td> <td>1.18</td> <td>1.19</td> <td>1.2%</td>	Smart homes	1.02	1.04	1.06	1.07	1.09	1.10	1.11	1.12	1.14	1.15	1.15	1.16	1.17	1.18	1.19	1.2%
Existing building electrification 0.20 0.20 0.21 </td <td>Building retrofits</td> <td>1.58</td> <td>1.63</td> <td>1.68</td> <td>1.73</td> <td>1.77</td> <td>1.81</td> <td>1.84</td> <td>1.88</td> <td>1.91</td> <td>1.94</td> <td>1.97</td> <td>2.00</td> <td>2.03</td> <td>2.06</td> <td>2.09</td> <td>2.2%</td>	Building retrofits	1.58	1.63	1.68	1.73	1.77	1.81	1.84	1.88	1.91	1.94	1.97	2.00	2.03	2.06	2.09	2.2%
Existing home electrification 0.47 0.49 0.51 0.53 0.57 0.59 0.61 0.62 0.64 0.65 0.66 0.68 0.70 0.71 0.73 Industrial current measures 3.23 3.44 3.66 3.66 4.08 4.28 4.44 4.69 4.15 4.35 4.63 4.68 4.48 4.90 5.12 5.26 5.80 5.61 6.02 6.25 6.37 Car and light truck efficiency 2.10 2.35 2.60 2.48 3.18 3.35 3.58 3.80 0.40 4.19 4.36 4.58 4.68 4.84 4.97 5.25 Reducing driving 1.90 1.55 1.57 1.68 1.66 1.68 1.70 1.72 1.74 1.77 1.82 1.84 1.97 4.13 1.44 1.51 1.51 1.57 1.63 1.65 1.66 1.68 1.78 1.77 1.79 1.82 1.84 1.97 1.82 1.84 1.97 1.82 1.88 1.97 1.65 1.62 1.88 1.97	Home retrofits	1.30	1.35	1.39	1.43	1.47	1.50	1.53	1.56	1.59	1.62	1.64	1.66	1.69	1.71	1.73	1.8%
industrial current measures 3.23 3.44 3.66 3.86 4.08 4.28 4.49 4.69 4.91 5.14 5.36 5.58 5.81 6.02 6.52 6.53 crand light truck efficiency 2.10 2.35 2.00 2.26 2.36 2.36 3.83 8.80 4.00 4.19 4.36 4.58 4.86 4.97 5.27 Truck and bus efficiency 1.20 1.37 1.54 1.71 1.87 2.04 2.19 2.35 2.52 2.26 2.28 2.33 3.28 2.43 2.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.48 3.49 3.48 3.49	Existing building electrification	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.2%
industrial current measures 3.23 3.44 3.66 3.86 4.08 4.29 4.49 4.69 4.91 5.14 5.36 5.58 5.61 6.02 6.53 6.53 Car and light truck efficiency 1.20 2.33 6.02 6.63 2.35 2.50 2.55 2.52 2.68 2.43 2.48 4.97 5.25 Reducing driving 1.90 1.95 1.99 2.02 2.06 2.19 2.55 2.52 2.68 2.44 2.99 3.14 3.23 3.28 3.28 3.28 2.49 2.44 4.99 Avaiton efficiency 1.12 1.00 1.95 1.99 2.02 2.06 2.16 1.66 1.68 1.70 1.72 1.74 1.77 1.79 1.82 1.84 1.99 2.04 2.05 0.81 0.82 0.81 0.82 0.81 0.82 0.81 0.82 0.81 0.81 0.77 0.75 0.77 0.75 0.77 0.78 0.77 0.78 0.77 0.75 0.77 0.75 0.77 7.7		0.47	0.49	0.51	0.53	0.55	0.57	0.59	0.61	0.62	0.64	0.65	0.67	0.68	0.70	0.71	0.7%
Car and light truck efficiency 2.10 2.35 2.60 2.86 3.12 3.36 3.80 4.00 4.19 4.36 4.53 4.68 4.84 4.97 5.27 Truck and bus efficiency 1.20 1.37 1.54 1.71 1.87 2.04 2.19 2.35 2.52 2.68 2.44 2.99 3.14 3.27 3.40 3.58 Reducing driving 1.90 1.95 1.99 2.02 2.05 2.02 2.52 2.38 2.43 2.48 2.48 2.49 2.48 2.48 2.49 2.48 2.48 2.49 2.48 2.48 2.48 1.44 1.52 1.60 1.69 1.78 1.88 1.97 2.06 2.16 2.26 2.42 2.44 1.44 1.82 1.44 1.52 1.60 1.69 1.78 1.88 1.97 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 0.75 0.74 <td< td=""><td>Industrial current measures</td><td>3.23</td><td>3.44</td><td>3.66</td><td>3.86</td><td>4.08</td><td>4.28</td><td>4.49</td><td>4.69</td><td>4.91</td><td>5.14</td><td>5.36</td><td>5.58</td><td>5.81</td><td>6.02</td><td>6.25</td><td>6.5%</td></td<>	Industrial current measures	3.23	3.44	3.66	3.86	4.08	4.28	4.49	4.69	4.91	5.14	5.36	5.58	5.81	6.02	6.25	6.5%
Car and light truck efficiency 2.10 2.35 2.60 2.86 3.12 3.36 3.80 4.00 4.19 4.36 4.53 4.68 4.84 4.97 5.23 Truck and bus efficiency 1.20 1.37 1.54 1.71 1.87 2.04 2.19 2.23 2.22 2.23 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.24 2.48 2.48 2.48 2.48 2.48 2.48 2.44 2.46 2.46 2.46 2.48 2.48 2.47 1.26 1.26 1.26 2.26 2.34 2.48 1.44 1.52 1.60 1.69 1.78 1.88 1.97 2.06 2.05 2.64 2.42 2.44 1.64 1.44 1.52 1.60 1.69 1.75 1.88 1.97 1.68 1.97 1.68 1.97 1.64 1.77 1.78 1.88 1.97 1.60 1.75 1.48 1.62 1.75 1.64 1.75	Industrial emerging technologies	1.84	2.12	2.41	2.69	2.97	3.25	3.52	3.79	4.07	4.35	4.63	4.90	5.18	5.44	5.72	5.9%
Truck and bus efficiency 1.20 1.37 1.54 1.71 1.87 2.04 2.19 2.35 2.26 2.68 2.49 2.33 2.33 2.33 2.33 2.43 2.44 2.64 Reducing driving 1.90 1.75 1.15 1.57 1.63 1.65 1.66 1.66 1.66 1.76 1.70 1.72 1.70 1.72 2.73 2.33 2.33 2.43 2.48 2.64 Aviation efficiency 1.12 1.20 1.28 1.36 1.44 1.52 1.60 1.68 1.70 1.72 1.70 1.70 0.75 0.74 0.73 0.75 0.74 0.73 0.75 0.74 0.73 0.75 0.75 0.83 0.84 0.83 0.84 0.84 0.84 0.75 0.83 0.85 0.84 0.40 0.75 0.83 0.84 0.84 0.44 0.75 0.75 0.75 0.76 0.76 0.77 0.76 0.74 0.75 0.57 0.57 0.57 0.50 0.50 0.55 0.55 0.55		2.10	2.35	2.60	2.86	3.12	3.36	3.58	3.80	4.00	4.19	4.36	4.53	4.68	4.84	4.97	5.2%
Reducing driving 1.90 1.95 1.90 2.02 2.06 2.09 2.12 2.16 2.00 2.25 2.29 2.33 2.38 2.43 2.48 2.63 Improving freight movement 1.32 1.12 1.15 1.65 1.66 1.68 1.70 1.72 1.74 1.77 1.79 1.82 2.43 2.43 2.43 2.43 2.43 2.43 2.44 2.45 2.45 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.45 2.44 2.	Truck and bus efficiency	1.20	1.37	1.54	1.71	1.87	2.04	2.19	2.35	2.52	2.68	2.84	2.99	3.14	3.27	3.40	3.5%
Improving freight movement 1.38 1.45 1.51 1.57 1.63 1.65 1.66 1.68 1.70 1.72 1.77 1.77 1.79 1.82 1.84 1.97 Awaiton efficiency 1.12 1.20 1.28 1.36 1.44 1.52 1.60 1.69 1.78 1.88 1.97 2.06 2.16 2.26 2.36 2.44 Electric distribution savings 0.76 0.75 0.82 0.88 0.80 0.84 0.82 0.88 0.81 0.82 0.84 0.82 0.84 0.82 0.84 0.82 0.84 0.82 0.84 0.42 0.79 0.78 0.77 0.75 0.70 0.70 0.78 0.77 0.75 0.70 0.70 0.78 0.77 0.75 0.70 0.78 0.77 0.75 0.70 0.83 0.70 0.71 0.78 0.79 0.83 0.70 0.71 0.70 0.83 0.83 0.70 0.71 0.70 0.78 0.79 0.70 0.71 0.70 0.78 0.79 0.71	Reducing driving																2.6%
Avation efficiency 1.12 1.20 1.20 1.28 1.36 1.44 1.52 1.60 1.69 1.78 1.88 1.97 2.06 2.16 2.26 2.36 2.43 Electric distribution savings 0.76 0.79 0.82 0.84 0.83 3.83 35.08 36.67 38.25 38.44 41.32 42.81 44.77 45.67 47.07 48.83 Baseline energy use (adjusted) 93.24 93.25 93.66 93.85 94.00 94.18 94.34 94.62 94.36 95.57 55.97 50.50 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 65.07 67.07 78 70.07 70.7		1.38	1.45	1.51	1.57	1.63	1.65	1.66	1.68	1.70	1.72	1.74	1.77	1.79	1.82	1.84	1.9%
Electric distribution savings 0.76 0.79 0.78 0.79 0.75 0.74 0.79 0.83 Total 24.67 26.48 26.48 28.26 30.30 31.83 33.48 35.68 36.67 38.25 39.48 41.32 42.81 44.27 45.67 47.67 48.89 Baseline energy use (adjusted) 93.24 93.37 93.56 93.66 93.68 94.00 94.8 94.26 94.89 95.25 95.57 95.57 95.67				1.28				1.60				1.97					2.4%
Total 24.67 26.48 28.26 30.03 31.83 33.48 35.08 36.67 38.25 93.84 41.32 42.81 44.27 45.67 47.07 48.83 Baseline energy use (adjusted) 93.24 93.37 93.56 93.66 93.85 94.00 94.18 94.34 94.62 94.98 95.25 95.57 95.97 96.02 96.53 Energy savings as a % of baseline 26.58 28.4% 30.2% 32.1% 33.9% 35.6% 37.3% 38.9% 40.4% 41.9% 43.4% 44.8% 46.1% 47.5% 48.8% Cog emissions reductions C </td <td>·</td> <td></td> <td></td> <td></td> <td></td> <td>0.87</td> <td></td> <td>0.84</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>0.73</td> <td>0.8%</td>	·					0.87		0.84								0.73	0.8%
Energy savings as a % of baseline 26.5% 28.4% 30.2% 32.1% 33.9% 35.6% 37.3% 38.9% 40.4% 41.9% 43.4% 44.8% 46.1% 47.5% 48.8% CD2 emissions reductions Image of the second seco		24.67	26.48	28.26	30.03	31.83	33.48	35.08		38.25	39.84	41.32	42.81	44.27	45.67	47.07	48.8%
Energy savings as a % of baseline 26.5% 28.4% 30.2% 32.1% 33.9% 35.6% 37.3% 38.9% 40.4% 41.9% 43.4% 44.8% 46.1% 47.5% 48.8% CD2 emissions reductions Image of the second seco	Baseline energy use (adjusted)		93.37	93.56	93.66	93.85	94.00	94.18		94.62		95.25		95.97		96.53	
Appliances and equipment1541621691751821881941982032062082102102102102104.89Zero energy new homes3135607888971061151231321331471541611683.89Zero energy new homes31354045551566267727681859093972.29Smart buildings6567687070777777777777787980818181828282199Building retrofits72747677778777777777667676767676767676767159Existing building electrification17181818191919202020212121212223541.59Existing building electrification13144152160168175183190198206214222233541.29Industrial emerging technologies77891001111221331431541641751851353733904074224235.19Industrial emerging technologies7789	Energy savings as a % of baseline	26.5%	28.4%	30.2%	32.1%	33.9%	35.6%	37.3%	38.9%	40.4%	41.9%	43.4%	44.8%	46.1%	47.5%	48.8%	
Zero energy new comm. buildings5361697888971061151231321391471541611683.88Zero energy new homes3135404551566267727681859093972.29Smart buildings6567687071727374757677777879791.89Smart homes4647 </td <td>CO₂ emissions reductions</td> <td></td>	CO ₂ emissions reductions																
Zero energy new homes31354045515662677276818590939322Smart buildings6567687071727374757677777879791.89Smart homes46474747474747474747474747444444474747474747474746461.19Building retrofits7274767778798080818181828282821.99Home retrofits596162636465666666666767676767671.59Existing home electrification17181818181919191020202121212223245.53Industrial current measures1351441521601681751831901882062142222292372445.61Industrial emerging technologies7789100111122133143154164175185195205214222292372445.61Industrial emerging technologies7789100111 </td <td>Appliances and equipment</td> <td>154</td> <td>162</td> <td>169</td> <td>175</td> <td>182</td> <td>188</td> <td>194</td> <td>198</td> <td>203</td> <td>206</td> <td>208</td> <td>210</td> <td>210</td> <td>210</td> <td>210</td> <td>4.8%</td>	Appliances and equipment	154	162	169	175	182	188	194	198	203	206	208	210	210	210	210	4.8%
Smart buildings 65 67 68 70 71 72 73 74 75 76 77 77 78 79 18 Smart buildings 66 67 67 77 77 77 77 78 79 18 19 1.19 Building retrofits 72 74 76 77 78 79 80 80 81 81 81 82 53 53 53 53 53	Zero energy new comm. buildings	53	61	69	78	88	97	106	115	123	132	139	147	154	161	168	3.8%
Smart homes4647	Zero energy new homes	31	35	40	45	51	56	62	67	72	76	81	85	90	93	97	2.2%
Building retrofits777777787778798080808181828282828219Home retrofits59616263646565656666676	Smart buildings	65	67	68	70	71	72	73	74	75	76	77	77	78	79	79	1.8%
Home retrofits5961626364656566666667 </td <td>Smart homes</td> <td>46</td> <td>47</td> <td>46</td> <td>46</td> <td>1.1%</td>	Smart homes	46	47	47	47	47	47	47	47	47	47	47	47	47	46	46	1.1%
Existing building electrification117118118118118119119119120120120121121121121121Existing home electrification383940424345464748495051525354129Industrial current measures135144152160168175183190198206214222229237244569Industrial emerging technologies7789100111122133143154164175185195205214223519Car and light truck efficiency18220422624927229531633635537330040742243745010.3Truck and bus efficiency1061021341491241241251251251251261261271271281293.09Improving freight movement90941011041041041051051051061061061061072.59Aviation efficiency74808590961021071131191251311381441511573.69Aviation efficiency7480859096102107113119125131 <td>Building retrofits</td> <td>72</td> <td>74</td> <td>76</td> <td>77</td> <td>78</td> <td>79</td> <td>80</td> <td>80</td> <td>81</td> <td>81</td> <td>81</td> <td>82</td> <td>82</td> <td>82</td> <td>82</td> <td>1.9%</td>	Building retrofits	72	74	76	77	78	79	80	80	81	81	81	82	82	82	82	1.9%
Existing home electrification 38 39 40 42 43 45 46 47 48 49 50 51 52 53 54 1.22 Industrial current measures 135 144 152 160 168 175 183 190 198 206 214 222 229 237 244 5.69 Industrial emerging technologies 77 89 100 111 122 133 143 154 164 175 185 195 205 214 223 5.19 Car and light truck efficiency 182 204 226 249 223 133 143 154 164 175 185 195 205 214 223 5.19 Car and light truck efficiency 182 204 226 249 233 143 149 163 177 191 205 214 224 243 450 1.03 Reducing driving 100 122 123 124 124 124 125 125	Home retrofits	59	61	62	63	64	65	65	66	66	67	67	67	67	67	67	1.5%
Industrial current measures 135 144 152 160 168 175 183 190 198 206 214 222 229 237 244 5.69 Industrial emerging technologies 77 89 100 111 122 133 143 154 164 175 185 195 205 214 223 5.19 Car and light truck efficiency 182 204 226 249 272 295 316 336 355 373 390 407 422 437 450 10.39 Truck and bus efficiency 106 120 134 149 163 177 191 205 216 216 127 212 304 7.09 Reducing driving 120 122 123 124 124 125 125 125 125 126 126 127 127 128 309 309 309 306 307 309 306 306 306 306 306 306 306 105 105 <t< td=""><td>Existing building electrification</td><td>17</td><td>18</td><td>18</td><td>18</td><td>19</td><td>19</td><td>19</td><td>20</td><td>20</td><td>20</td><td>21</td><td>21</td><td>21</td><td>21</td><td>22</td><td>0.5%</td></t<>	Existing building electrification	17	18	18	18	19	19	19	20	20	20	21	21	21	21	22	0.5%
Industrial emerging technologies 77 89 100 111 122 133 143 154 164 175 185 195 205 214 228 5.19 Car and light truck efficiency 182 204 226 249 272 295 316 336 355 373 300 407 422 437 450 10.39 Truck and bus efficiency 106 120 134 149 163 177 191 205 219 234 249 263 277 291 304 709 Reducing driving 120 122 123 124 124 125 125 125 125 125 125 125 126 127 127 128 129 300 Improving freight movement 709 94 98 101 104 104 105 105 105 106 106 107 258 Aviation efficiency 74 83 30 301 301 30 29 28 27 26	Existing home electrification	38	39	40	42	43	45	46	47	48	49	50	51	52	53	54	1.2%
Car and light truck efficiency18220422624927229531633635537339040742243745010.39Truck and bus efficiency1061201341491631771912052192342492632772913047.09Reducing driving1201221231241241241251251251261261271271281293.09Improving freight movement9094981011041041051051051051061061061072.59Aviation efficiency74808590961021071131191251311381441511573.69Electric distribution savings32323333343331302.992.4282.762.532.322.352.4682.4992.4612.59Total1,3521,4481,5411,6321,7261,8111,8921,9722,0502,1282,1992,2682,3662,3992,4615.59Baseline energy CO2 emissions4,5554,5284,5094,4884,4744,4574,4434,4294,4194,4134,4004,3884,3824,3644,353	Industrial current measures	135	144	152	160	168	175	183	190	198	206	214	222	229	237	244	5.6%
Truck and bus efficiency1061201341491631771912052192342492632772913047.07Reducing driving1201221231241241241251251251261261271271281293.09Improving freight movement9094981011041041041051051051061061061061072.59Aviation efficiency74808590961021071131191251311381441511573.69Electric distribution savings3232333334333130292827262523220.59Total1,3521,4481,5411,6321,7261,8111,8921,9722,0502,1282,1992,2682,3662,3992,46156.59Baseline energy CO2 emissions4,5584,5584,5094,4884,4744,4574,4434,4294,4134,4004,3884,3824,3644,353	Industrial emerging technologies	77	89	100	111	122	133	143	154	164	175	185	195	205	214	223	5.1%
Reducing driving 120 122 123 124 124 125 125 125 126 126 127 127 128 129 3.09 Improving freight movement 90 94 98 101 104 104 105 105 105 106 106 106 106 106 106 107 2.59 Aviation efficiency 74 80 85 90 96 102 107 113 119 125 131 138 144 151 157 3.69 Electric distribution savings 32 32 33 33 33 33 33 33 30 209 2.89 2.76 2.58 2.39 2.461 55.59 Baseline energy CO ₂ emissions 4,555 4,558 4,509 4,488 4,474 4,457 4,443 4,409 4,413 4,400 4,388 4,382 4,364 4,355	Car and light truck efficiency	182	204	226	249	272	295	316	336	355	373	390	407	422	437	450	10.3%
Reducing driving 120 122 123 124 124 125 125 125 126 126 127 127 128 129 3.09 Improving freight movement 90 94 98 101 104 104 105 105 105 106 106 106 106 106 107 2.59 Aviation efficiency 74 80 85 90 96 102 107 113 119 125 131 138 144 151 157 3.69 Electric distribution savings 32 32 33 33 34 33 31 30 209 2.89 2.78 2.59	Truck and bus efficiency	106	120	134	149	163	177	191	205	219	234	249	263	277	291	304	7.0%
Aviation efficiency 74 80 85 90 96 102 107 113 119 125 131 138 144 151 157 3.69 Electric distribution savings 32 32 33 33 34 33 31 30 29 28 27 26 25 23 22 0.59 Total 1,352 1,448 1,541 1,632 1,726 1,811 1,892 1,972 2,050 2,128 2,199 2,268 2,336 2,399 2,461 56.59 Baseline energy CO ₂ emissions 4,554 4,528 4,509 4,488 4,474 4,457 4,443 4,400 4,388 4,382 4,364 4,353	Reducing driving	120	122	123	124	124	124	125	125	125	126	126	127	127	128	129	3.0%
Aviation efficiency 74 80 85 90 96 102 107 113 119 125 131 138 144 151 157 3.69 Electric distribution savings 32 32 33 33 34 33 31 30 29 28 27 26 25 23 22 0.59 Total 1,352 1,448 1,541 1,632 1,726 1,811 1,892 1,972 2,050 2,128 2,199 2,268 2,336 2,399 2,461 56.59 Baseline energy CO ₂ emissions 4,554 4,528 4,509 4,488 4,474 4,457 4,443 4,400 4,388 4,382 4,364 4,353	Improving freight movement	90	94	98	101	104	104	104	105	105	105	105	106	106	106	107	2.5%
Electric distribution savings 32 32 33 34 33 34	Aviation efficiency	74	80	85	90	96	102	107	113		125	131	138	144	151	157	3.6%
Total 1,352 1,448 1,541 1,632 1,726 1,811 1,892 1,972 2,050 2,128 2,199 2,268 2,336 2,399 2,461 56.59 Baseline energy CO ₂ emissions 4,555 4,528 4,509 4,488 4,474 4,457 4,443 4,409 4,348 4,382 4,364 4,355	Electric distribution savings	32	32	33	33	34	33	31	30	29	28	27	26	25	23	22	0.5%
Baseline energy CO ₂ emissions 4,545 4,528 4,509 4,488 4,474 4,457 4,443 4,429 4,419 4,413 4,400 4,388 4,382 4,364 4,353	0	1,352	1,448	1,541	1,632	1,726	1,811	1,892	1,972	2,050	2,128	2,199	2,268	2,336	2,399	2,461	56.5%
	Baseline energy CO ₂ emissions													,			
		,		,	,	,	,	,	,	,	,	,	,	,			

Table B2. Key assumptions and sources by opportunity

Measure	Baseline energy use	Savings	% applies to
Appliance and equipment efficiency	From deLaski et al. 2016 and Mauer, deLaski, and DiMascio 2017.	Specific savings numbers from deLaski et al. 2016 and Mauer, deLaski, and DiMascio 2017, with updates provided by Mauer (personal communication). These cover standards set until about 2030. Estimated that savings continue to grow in 2030s and 2040s at half the rate they grew in the 2020s and 2030s. Multiplied savings by 125% to add additional savings from ENERGY STAR products, which is somewhat less than the average ratio of ENERGY STAR product savings to appliance and equipment standard savings over the 2005–2015 period (Nadel 2016b).	From deLaski et al. 2016 and Mauer, deLaski, and DiMascio 2017.
Zero net energy (ZNE) new buildings and homes	For homes, used AEO construction assumptions, which average 1.55 million new homes/year. For buildings, new floor area in AEO. Reference case energy use from that of building stock in AEO.	For first tier 28% average for homes, 30% for commercial buildings (reduced from 37% and 40% in York et al. 2015a), applied to 80% of energy use. For second tier 70% average applied to all energy use. Second tier homes and buildings use 50% electricity and 50% renewables (still counted in energy use).	Both homes and buildings ramp up from 7% in 2020 (first tier) and 15% in 2031 (second tier) to 90% participation in 2040, but 10% of homes and buildings are either energy intensive and not ZNE or in states without such codes.
Smart buildings and homes	From AEO, subtracting savings from the above two measures.	20% in commercial buildings (reduction from 28% in Rogers et al. 2013), 15% in homes (reduction from 17% in King 2018 plus 5% for AMI from York et al. 2015a).	Gradual ramp-up to 95% of commercial buildings and 80% of homes by 2050.
Home and building retrofits	From <i>AEO</i> , subtracting savings from the above three measures.	30% on average—more than a standard retrofit (which saves about 20%), but less than a deep retrofit (which saves about 50%).	Gradual ramp-up to 80% of commercial buildings and 65% of homes by 2050.
Electrification of existing buildings	From AEO using space and water heating energy use, but subtracting all prior building measure savings.	For homes, 21% in 2020, ramping up to 51%; savings ramp up over time as heat rate improves (from Nadel 2018a) using CCGT for 2020 and 50% renewables, 50% natural gas for 2050. For commercial buildings, 29% from Kim et al. 2017.	By 2050, 50% of homes and 45% of commercial buildings from high scenario in Mai et al. 2018.

Measure	Baseline energy use	Savings	% applies to
Industrial efficiency improvements	From AEO, subtracting savings from industrial share of equipment standards.	20% for current measures, 15% more for emerging measures starting in 2025, and a further 15% for structural measures starting in 2035.	By 2050, 80% for current measures, 65% for emerging measures (starting in 2025), and 50% for structural measures (starting in 2035).
Light-duty vehicle fuel economy	From AEO.	EVs ramp up to 80% of new vehicle sales by 2042, with EV efficiency starting at 3.4 miles/kWh and increasing 2%/year to 2025, 1.5%/year to 2030, and 0.5%/year thereafter. Remaining vehicles will remain ICE vehicles. For non-EVs, fuel economy increases 4%/year from 2026–2030 and 2%/year thereafter. Assume 2025 CAFE standards remain in place (in baseline) and 15-year vehicle life.	100%, as savings to the left are an average for all vehicles, considering both high savers and zero savers.
Heavy-duty vehicle fuel economy	From AEO.	EVs ramp up to 45% of the vehicle stock (derived by ACEEE from BNEF 2019), saving 28-47% (based on Gao et al. 2018, with a simple average over vehicle categories, and adjusted for heat rate changes). New ICE vehicles improve 2%/year relative to baseline from 2028 until reaching 30% savings in 2045 and then fuel economy levels off (incorporated into stock assuming an 11-year life).	100%, as savings to the left are an average for all vehicles, considering both high savers and zero savers.
Reductions in passenger vehicle miles traveled	From AEO, subtracting savings from fuel economy,	30%; rationale discussed in text,	100%, as savings to the left are an average for all vehicles.
Reductions in freight transport energy use	From AEO, subtracting savings from fuel economy,	25%; rationale discussed in text,	100%, as savings to the left are an average for all shipments.
Aviation efficiency improvements	From AEO, using jet fuel use to include military aviation,	Ramp up to 32% in 2035 and 56% in 2050 (from Greene and Plotkin 2011), but adjust for 8% improvement in 2035 and 9% improvement in 2050 implicit in <i>AEO</i> 2019 relative to the base used by Greene and Plotkin.	100%, as savings to the left are an average for all users.

Measure	Baseline energy use	Savings	% applies to
Reductions in CVR and T&D loss	Energy use for electricity from <i>AEO</i> , subtracting electric savings from above measures and adding additional energy use for EVs and building electrification.	In 2020, 2.3% reduction for CVR (from York et al. 2015a), plus 1.5% reduction from reduced T&D losses. Ramp up to 5% total savings starting in 2025 based on improved optimization. Explained in text.	Ramp up to 80% of grid by 2040; measures may not apply or are too difficult to apply to remaining 20% of the grid.

Appendix C. Policy Analysis Details

Table C1. Energy savings and CO $_2$ emissions reductions by measure and year

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Primary energy savings																
Appliance standards	0.06	0.13	0.20	0.31	0.51	0.70	0.86	1.02	1.18	1.37	1.61	1.86	2.10	2.34	2.61	2.8
Building codes: commercial	0.00	0.02	0.04	0.07	0.12	0.17	0.23	0.30	0.37	0.45	0.53	0.62	0.72	0.82	0.92	1.0
Building codes: residential	0.00	0.01	0.02	0.03	0.05	0.08	0.11	0.14	0.18	0.22	0.26	0.31	0.36	0.41	0.46	0.5
Commercial building standard	0.00	0.00	0.16	0.31	0.49	0.66	0.84	1.05	1.19	1.33	1.45	1.57	1.70	1.81	1.92	2.0
Home sale & rental standard	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.05	0.06	0.07	0.11	0.14	0.16	0.18	0.20	0.2
Building electrification programs	0.02	0.04	0.06	0.08	0.09	0.11	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.2
Home electrification programs	0.03	0.07	0.10	0.14	0.17	0.21	0.24	0.28	0.31	0.34	0.37	0.40	0.43	0.46	0.49	0.5
Industrial near-term policies	0.17	0.34	0.51	0.67	0.83	0.98	1.13	1.30	1.47	1.63	1.80	1.97	2.14	2.31	2.48	2.6
Industrial long-term policies	0.00	0.00	0.00	0.00	0.00	0.13	0.25	0.38	0.50	0.63	0.75	0.87	0.99	1.11	1.23	1.5
Car and light truck standards	0.01	0.03	0.05	0.09	0.13	0.18	0.26	0.36	0.48	0.63	0.80	0.99	1.19	1.40	1.64	1.8
Truck and bus standards	0.02	0.05	0.08	0.10	0.13	0.16	0.21	0.25	0.32	0.39	0.46	0.57	0.69	0.82	0.96	1.1
Road use fee: light-duty	0.00	0.00	0.00	0.17	0.34	0.49	0.63	0.76	0.76	0.74	0.74	0.74	0.73	0.73	0.73	0.7
Road use fee: heavy-duty	0.00	0.00	0.00	0.07	0.14	0.20	0.27	0.32	0.33	0.33	0.33	0.34	0.34	0.35	0.35	0.3
Airplane standards	0.04	0.08	0.12	0.16	0.20	0.25	0.29	0.34	0.38	0.43	0.48	0.53	0.57	0.62	0.68	0.7
Electric distribution programs	0.05	0.09	0.14	0.20	0.26	0.33	0.38	0.42	0.47	0.51	0.55	0.58	0.62	0.66	0.70	0.7
Utility programs (EERS)	0.00	0.04	0.16	0.36	0.62	0.95	1.30	1.62	1.92	2.18	2.40	2.60	2.78	2.92	3.04	3.1
Total	0.41	0.89	1.63	2.77	4.10	5.61	7.15	8.72	10.07	11.40	12.82	14.27	15.73	17.15	18.63	20.2
Baseline energy use	96.53	96.11	95.85	95.35	95.03	94.64	94.43	94.26	94.27	93.96	93.64	93.57	93.49	93.31	93.24	93.2
Energy savings as % of baseline	0.4%	0.9%	1.7%	2.9%	4.3%	5.9%	7.6%	9.3%	10.7%	12.1%	13.7%	15.3%	16.8%	18.4%	20.0%	21.7%
CO ₂ emissions reductions																
Appliance standards	3	6	10	15	25	34	42	49	56	65	75	86	97	107	119	12
Building codes: commercial	0	1	2	4	6	9	11	15	18	22	26	30	35	40	46	5
Building codes: residential	0	0	1	2	3	4	5	7	9	10	12	14	17	20	23	2
Commercial building standard	0	0	8	16	25	34	42	53	59	65	71	76	82	87	92	9
Home sale & rental standard	0	0	0	0	0	1	2	2	3	3	5	7	8	9	10	1
Building electrification programs	2	4	5	7	9	10	12	13	14	15	16	17	18	18	19	2
Home electrification programs	3	7	10	13	16	20	23	26	29	32	34	36	38	40	42	4
Industrial near-term policies	8	15	22	29	36	42	48	55	62	68	75	81	88	94	101	10
Industrial long-term policies	0	0	0	0	0	5	11	16	22	27	32	37	42	46	51	6
Car and light truck standards	1	3	5	8	12	17	24	33	44	57	71	88	105	124	144	16
Truck and bus standards	2	5	7	9	12	14	19	23	28	34	41	50	60	70	81	9
Road use fee: light-duty	0	0	0	12	23	33	42	50	50	49	48	47	47	46	45	4
Road use fee: heavy-duty	0	0	0	5	9	14	18	21	22	22	22	22	22	22	22	2
Airplane standards	3	6	8	11	14	17	20	23	26	29	32	36	39	43	46	5
Electric distribution programs	2	4	7	10	13	16	18	20	22	23	25	26	28	29	30	3
Utility programs (EERS)	0	2	8	18	31	46	63	79	92	104	113	121	129	135	139	14
Total	24	52	93	159	232	315	399	484	556	625	698	775	854	930	1,010	1,09
Baseline energy CO ₂ emissions	5,116	5,050	5,038	4,991	4,939	4,902	4,872	4,835	4,808	4,758	4,710	4,683	4,664	4,628	4,601	4,57
CO ₂ reductions as % of baseline	0.5%	1.0%	1.8%	3.2%	4.7%	6.4%	8.2%	10.0%	11.6%	13.1%	14.8%	16.6%	18.3%	20.1%	21.9%	24.0%

	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Primary energy savings															
Appliance standards	3.09	3.29	3.45	3.62	3.81	3.97	4.13	4.28	4.43	4.57	4.68	4.77	4.86	4.93	5.00
Building codes: commercial	1.14	1.26	1.38	1.50	1.62	1.75	1.88	2.02	2.16	2.30	2.44	2.58	2.73	2.89	3.04
Building codes: residential	0.58	0.64	0.70	0.77	0.84	0.90	0.98	1.05	1.12	1.20	1.27	1.35	1.43	1.51	1.59
Commercial building standard	2.16	2.28	2.40	2.51	2.62	2.74	2.86	2.98	3.10	3.23	3.36	3.49	3.63	3.78	3.93
Home sale & rental standard	0.30	0.34	0.37	0.40	0.46	0.50	0.54	0.58	0.61	0.67	0.72	0.76	0.80	0.83	0.88
Building electrification programs	0.22	0.22	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.22	0.22	0.21
Home electrification programs	0.54	0.57	0.59	0.61	0.64	0.66	0.68	0.70	0.73	0.74	0.76	0.77	0.78	0.80	0.80
Industrial near-term policies	2.84	3.03	3.23	3.42	3.63	3.83	4.03	4.24	4.46	4.68	4.90	5.13	5.36	5.58	5.82
Industrial long-term policies	1.78	2.05	2.33	2.60	2.87	3.14	3.41	3.67	3.93	4.21	4.47	4.74	5.01	5.27	5.53
Car and light truck standards	2.11	2.36	2.61	2.87	3.13	3.38	3.60	3.82	4.01	4.20	4.37	4.54	4.68	4.83	4.97
Truck and bus standards	1.25	1.42	1.59	1.77	1.94	2.10	2.26	2.43	2.60	2.77	2.92	3.08	3.22	3.36	3.50
Road use fee: light-duty	0.72	0.73	0.73	0.72	0.72	0.73	0.74	0.76	0.77	0.78	0.79	0.79	0.80	0.80	0.81
Road use fee: heavy-duty	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.40	0.41	0.41	0.41	0.42	0.42	0.42	0.42
Airplane standards	0.80	0.88	0.96	1.05	1.13	1.21	1.30	1.39	1.48	1.57	1.66	1.76	1.86	1.96	2.06
Electric distribution programs	0.76	0.80	0.83	0.86	0.90	0.88	0.87	0.86	0.85	0.84	0.83	0.82	0.81	0.80	0.79
Utility programs (EERS)	3.19	3.24	3.26	3.26	3.25	3.22	3.18	3.12	3.07	3.00	2.93	2.87	2.80	2.73	2.66
Total	21.86	23.48	25.03	26.57	28.16	29.65	31.10	32.52	33.95	35.40	36.74	38.09	39.43	40.71	42.01
Baseline energy use	93.24	93.37	93.56	93.66	93.85	94.00	94.18	94.34	94.62	94.98	95.25	95.57	95.97	96.20	96.53
Energy savings as % of baseline	23.4%	25.1%	26.8%	28.4%	30.0%	31.5%	33.0%	34.5%	35.9%	37.3%	38.6%	39.9%	41.1%	42.3%	43.5%
CO ₂ emissions reductions															
Appliance standards	137	144	150	155	162	167	172	176	179	183	184	185	186	186	186
Building codes: commercial	58	64	71	78	85	92	99	106	114	121	128	134	141	148	154
Building codes: residential	29	32	36	39	43	47	50	54	58	61	65	68	72	75	79
Commercial building standard	101	106	110	114	118	122	126	130	134	138	141	145	149	153	157
Home sale & rental standard	14	16	17	18	21	22	24	25	26	29	30	32	33	34	36
Building electrification programs	20	20	20	21	21	21	22	22	22	22	22	22	22	22	22
Home electrification programs	45	47	48	49	51	53	54	56	57	58	59	60	61	62	62
Industrial near-term policies	115	122	129	136	144	151	159	166	174	182	190	197	205	213	220
Industrial long-term policies	73	84	95	105	116	126	135	145	155	165	175	184	193	202	211
Car and light truck standards	186	208	231	254	277	300	321	341	360	378	395	411	426	440	453
Truck and bus standards	106	119	133	148	162	176	189	203	218	232	246	260	273	286	299
Road use fee: light-duty	43	42	42	41	40	39	39	39	39	39	39	38	38	37	37
Road use fee: heavy-duty	22	23	23	23	23	23	22	22	23	23	22	22	22	21	21
Airplane standards	55	60	66	71	77	83	88	94	100	107	113	120	126	133	140
Electric distribution programs	32	33	34	34	35	34	33	32	31	30	29	27	27	25	24
															101
Utility programs (EERS)	143	143	143	141	139	137	133	130	126	122	118	113	110	105	101
Utility programs (EERS) Total	143 1,179	143 1,264	143 1,346	141 1,427	139 1,511	137 1,591	133 1,667	130 1,742	126 1,815	122 1,889	118 1,956	113 2,020	110 2,084	105 2,143	-
	-	-	-												101 2,203 4,353

Policy	Total energy (quads)	CO ₂ emissions (MMT)	Electricity (TWh)	Natural gas (Tbtus)	Oil (mbd)	Energy bill (\$ billion)
Appliance standards	5.00	186	546	1,313	-	81
Building codes: commercial	3.04	154	344	1,164	0.10	54
Building codes: residential	1.59	79	168	706	0.02	34
Commercial building standard	3.93	157	386	1,086	0.09	57
Home sale & rental standard	0.88	36	80	300	0.01	16
Building electrification programs	0.21	22	-56	383	0.06	1
Home electrification programs	0.80	62	-95	953	0.15	10
Industrial near-term policies	5.82	220	155	2,546	0.52	56
Industrial long-term policies	5.53	211	156	2,445	0.48	53
Car and light truck standards	4.97	453	-473	-	3.12	146
Truck and bus standards	3.50	299	-251	-	1.99	95
Road use fee: light-duty	0.81	37	75	-	0.12	17
Road use fee: heavy-duty	0.42	21	33	-	0.08	9
Airplane standards	2.06	140	-	-	0.80	39
Electric distribution programs	0.79	24	121	_	-	_
Utility programs (EERS)	2.66	101	278	775	_	35
Total	42.96	2,337	1,468	11,672	7.53	704

Table C2. Energy savings by fuel, CO_2 emissions reductions, and energy cost savings by policy in 2050

Table C3. Key assumptions and sources by policy

We did the opportunity analysis on a primary energy basis but the policy analysis by fuel, resulting in slight differences in the savings numbers.

Measure	Baseline energy use	Savings	% applies to		
Appliance and equipment standards and ENERGY STAR		nt opportunity, but savings reduced by 25% of overlap ERGY STAR savings reduced by 25% of overlap with EE			
Building energy codes	Same as ZNE residential and commercial opportunity, except shifted large multifamily construction to commercial.	For new homes, start at 10% savings and decrease energy use by further 3% each year (reaching 64% savings); for new commercial buildings, start at 20% savings and decrease energy use 2% each year (reaching 56%). Based on current model codes and reducing energy use 10% in each three-year code cycle, versus baseline savings of 1% every three years. Assume opportunity analysis second-tier energy use is at that mix; balance of energy use is at baseline mix.	Start at 80% for homes and 50% for commercial buildings based on current compliance (Athalye et al. 2016); losses decrease by 10% each year. Savings and compliance averaged over five years to incorporate gradual adoption of codes.		
Commercial building energy use benchmarking and standard	From AEO.	Ramp up starting in 2022 to 12% in 2027, 23% in 2037, 32% in 2047, and 35% in 2050, based on savings for office buildings to reach ENERGY STAR benchmarks of 50, 60, and 70. Savings reduced by 25% of overlap with commercial appliance standards and EERS.	Cover 56% in 2022, an additional 68% delayed two years, and 13% delayed three years, based on energy use of buildings over 50,000, 25,000, and 10,000 sq. ft. in 2012 CBECS (EIA 2016b).		
Home energy efficiency labeling and requirement for sale or lease	From AEO, subtracting savings from appliance standards, and subtracting large multifamily use based on RECS (EIA 2018).	1.7% in 2025, ramping up every five years to 4.7%, 9.0%, 12.7%, 15.7%, and 18.1%. Based on savings to reach Home Energy Scores of 2–6 (but with no score increasing by more than 3) in simple average over HES regions. Savings reduced by 25% of overlap with residential EERS.	Applied separately to energy use of rented and owned homes based on RECS, applied to 25% of rental and 5.9% of owned homes each year based on typical turnover and recent sales rates.		
Industrial efficiency programs and research	Same as industrial opportunity, b	ut current-measure savings reduced by 25% of overla	o with industrial EERS.		
Light-duty vehicle fuel economy standards					

Measure	Baseline energy use	Savings	% applies to				
Heavy-duty vehicle fuel economy standards	Same as heavy-duty vehicle oppo	rtunity.					
Light-duty vehicle miles traveled and congestion fees	From AEO, subtracting savings from fuel economy.	An added driving cost of 3 cents/mile, applied assuming a constant demand elasticity of -0.1 (analogous to 10% rebound), stock vehicle fuel economies incorporating the fuel economy standards, and electricity and gas prices from <i>AEO</i> . Savings doubled to include congestion pricing.	100%				
Heavy-duty vehicle miles traveled and congestion fees	From AEO, subtracting savings from fuel economy.	Based on light-duty vehicle percentage savings, but reduced for –0.08 elasticity (analogous to 8% heavy-duty rebound).	100%				
Airplane efficiency standard	Same as aviation opportunity, but in 2050).	t only include airplane efficiency, not system improven	nents (25% savings in 2035 and 50%				
Incentives for electri- fication of homes and commercial buildings	Same as electrification opportuni	ty, but subtracting all other policy heating equipment s	savings from baseline.				
Regulation of conservation voltage reduction and of transmission and distribution losses	Same as opportunity, but adjusting baseline for all other policy electricity savings and electrification.						

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Measure	Baseline energy use	Savings	% applies to
Energy efficiency resource standard (EERS)	From AEO for electricity and natural gas use, adjusted for all other policy savings and fuel shifts (including electricity use of EVs).	Ramp up to 2% new electricity savings and 1% new natural gas savings each year starting in 2025, compared with 0.7% electricity and 0.4% natural gas savings in the reference case. Savings are relative to the average use in the three previous years in the respective cases. Assume an average life of 10.6 years for electric measures and 16.1 years for natural gas measures, with straight-line decay of savings. Savings reduced by 25% of overlap with added ENERGY STAR savings, existing home and commercial building standards, and current industrial measures.	100%