Pathway to Cutting Energy Use and Carbon Emissions in Half

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Prior to ACEEE, Steve planned and evaluated energy efficiency programs for New England Electric, a major electric utility; directed energy programs for the Massachusetts Audubon Society, the state's largest environmental organization; and ran energy programs for a community organization working on housing rehabilitation in the poorest neighborhoods of New Haven, Connecticut. Steve earned a master of science in energy management from the New York Institute of Technology and a master of arts in environmental studies and a bachelor of arts in government from Wesleyan University.

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Executive Summary

INTRODUCTION

In a 2012 report, the American Council for an Energy-Efficient Economy (ACEEE) looked at energy efficiency opportunities out to 2050 and found that energy efficiency could reduce projected 2050 US energy use by 40–60%. Based on this, ACEEE established a strategic goal to reduce projected 2050 energy use by 50%. If we can achieve 50% energy savings from energy efficiency, greenhouse gas (GHG) emissions would likely fall by a similar percentage, putting the United States well on the path to achieving its long-term goal of reducing these emissions by at least 80% by 2050.

Five years have passed since our original analysis, and we thought it would be useful to check on our progress toward this goal and ask whether the goal still seems reasonable. For example, looking at progress since our 2012 analysis, we find that in recent years energy use has been stable, reversing historical growth. However, if we want actual declines in energy use, we will need to redouble our efforts. We also thought it would be useful to update the baseline to 2016 projections in view of changes over the past five years such as shifts in the demand for electricity and how this electricity is generated. Finally, we decided to look at potential savings in terms of packages of efficiency measures in order to more clearly outline what needs to be done to reach this 2050 goal.

ANALYSIS

Our analytical approach was to compare the reference case in the *2016 Annual Energy Outlook* (2016 AEO), prepared by the Energy Information Administration (EIA), to an energy efficiency case we prepared that estimated the energy savings from 13 packages of energy efficiency measures:

- Appliance and equipment efficiency
- Zero net energy (ZNE) new buildings and homes
- Smart buildings and homes
- Home and building retrofits
- Behavior change in buildings
- Industrial efficiency improvements
- Combined heat and power (CHP) systems
- Light and heavy duty vehicle fuel economy improvements
- Reductions in passenger vehicle miles traveled (VMT)
- Reductions in freight transport energy use
- Aviation efficiency improvements
- Conservation voltage reduction and reductions in losses from transmission and distribution systems
- Reductions in power plant heat rates

Our analysis accounts for both overlap between measures and direct and indirect rebound effects. We consider how much energy can be saved in 2040, and whether these savings put us on a path to cut projected US energy use in half by 2050.

RESULTS

We find that, taken together, the energy efficiency measures we examined would reduce 2040 energy use by 34%, bringing it down to 66 quads, and approximately putting us on a path to achieve the 50% energy savings by 2050 goal. We also looked at carbon dioxide (CO_2) emissions, finding that 2040 CO_2 emissions would be reduced by 35% relative to the 2040 reference case and also put carbon emissions on a 50% reduction path. The United States and many other countries are targeting GHG emissions reductions of 80% or more relative to 2005 levels. For the United States, emissions in our 2040 efficiency case are 45% below 2005 levels. Additional emissions reductions will be needed to reach the 80% reduction goal, including additional efficiency savings in the 2040–2050 period, as well as additional non-efficiency measures, including increased use of zero-emissions energy sources (e.g., renewable and nuclear energy), possible use of carbon capture and storage techniques, and reductions in GHGs besides CO_2 (e.g., methane and halons).

Energy and emissions reductions can be found in each of the major sectors—residential, commercial, industrial, transportation, and power. Savings and emissions reductions are largest in the transportation sector, followed closely by the commercial, industrial, and residential sectors. Savings are smallest in the power sector, because our power sector savings are solely from efficiency. Transportation measures generally contribute a higher percentage to emissions reductions than to energy use reductions due to the relatively high carbon content of most transportation fuels.

Each of the 13 measures we examined contributes to putting us on the 50% energy use reduction path. The largest savings come from the industrial efficiency package, followed by ZNE new homes and buildings, vehicle fuel economy improvements, appliance and equipment efficiency, and home and commercial building retrofits. Figure ES1 shows the proportion of the total energy use reduction from each measure. The allocation of emissions reductions by measure is similar, except that transportation measures contribute disproportionately to emissions reductions.

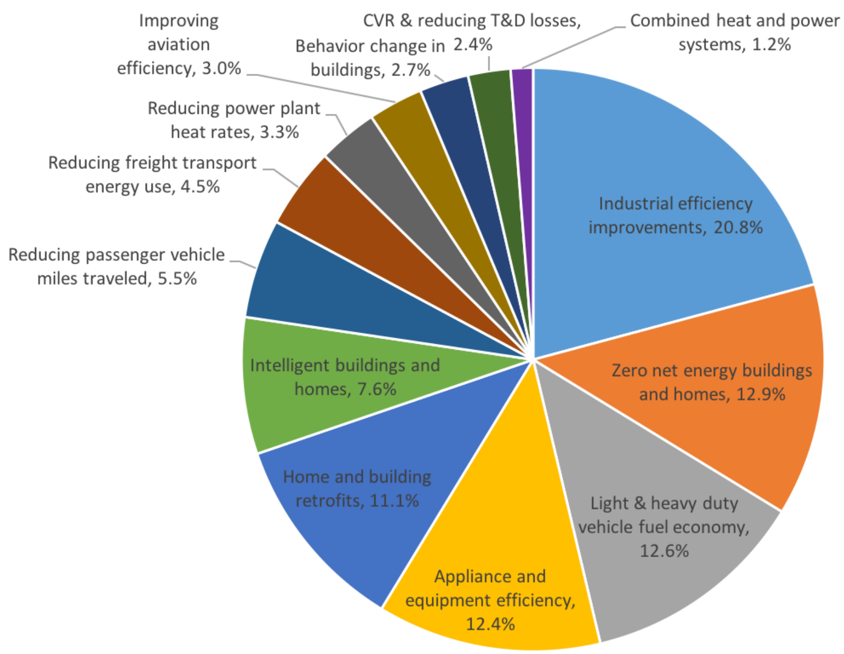

Figure ES1. Allocation of energy savings among measures

In addition, we prepared three alternative scenarios: (1) assuming greater use of renewable energy than EIA projects, (2) looking at savings relative to an AEO 2011 base (instead of the AEO 2016 base), and (3) accounting for energy efficiency incorporated into the 2016 AEO in our analysis. All three alternative scenarios would increase energy savings, putting us slightly ahead of the pace needed to achieve 50% energy savings by 2050.

CONCLUSIONS

Our analysis finds that the 13 efficiency measures we examine, if pursued aggressively, would reduce 2040 energy use by 34%, putting the United States on a path to reduce 2050 energy use by 50% relative to currently predicted levels. Achieving these energy efficiency savings will require expansion of energy efficiency efforts beyond business-as-usual, including

- New building codes, equipment efficiency standards, and ENERGY STAR® specifications
- Substantial improvements to existing factories, homes, commercial buildings, transmission and distribution systems, and power plants
- Efforts to better manage freight and aviation energy use, reduce vehicle miles traveled, and spur changes in how individuals use energy at home, at work, and in transport

We must rigorously pursue all of these opportunities, with a particular emphasis on those with the largest savings. We have examined savings through 2040, but to achieve the 2050 goal will require continuing efficiency efforts—including those profiled here—for another decade, improving these efforts based on lessons learned over the 2016–2040 period, and pursuing new energy-saving opportunities that emerge over the next two decades. We must also continue to invest in research and development to identify new efficiency measures; these will provide additional savings opportunities that we can only imagine today and that will complement the examined measures. Through these steps, we can reduce energy use, reduce emissions, and strengthen our economy.

Introduction

In an early 2012 report, the American Council for an Energy-Efficient Economy (ACEEE) looked at energy efficiency opportunities out to 2050, finding that energy efficiency could reduce projected 2050 US energy use by 40–60% (Laitner et al. 2012). Based on this, ACEEE established a strategic goal to reduce projected 2050 energy use by 50%. If we can achieve 50% energy savings from energy efficiency, greenhouse gas (GHG) emissions would likely fall by a similar percentage, putting the United States well on the path to achieving its long-term goal of reducing emissions by at least 80% by 2050.[1]

Five years have passed since our original analysis, and we thought it would be useful to check on our progress toward this goal and ask whether the goal still seems reasonable. We also thought it would be useful to update the baseline to 2016 projections in view of recent changes such as shifts in the demand for electricity and how this electricity is generated. Finally, we decided to look at potential savings in terms of packages of efficiency measures in order to more clearly outline what needs to be done to reach this 2050 goal.

To achieve these objectives, we prepared several analyses. First, we briefly examine progress since our 2012 analysis. Second, we conduct a new analysis on whether a 50% energy use reduction by 2050 remains feasible and, if so, what it might take to achieve this goal. This analysis is the primary focus of this paper. Finally, we present several variations on this new analysis.

Progress Since Our 2012 Analysis

In 2012 ACEEE published an analysis (Laitner et al. 2012) that used the Energy Information Administration's (EIA's) *2011 Annual Energy Outlook* (2011 AEO) as a base.[2] Since then, US energy use has been essentially flat, with 2010 and 2015 energy use nearly identical at 97.4 quadrillion Btus of annual consumption (quads) each year.[3] Consumption is down from the peak of 101 quads in 2007 (just before the Great Recession). Although energy use grew at a compound average of 0.7% per year in the decade before the Great Recession, in the years since the recession ended in mid-2009, consumption has been flat (see figure 1). In the Results section, we examine changes in the 2050 projections between 2011 and 2016; these changes show progress over the past five years. Still, while progress has been made to reverse the historical growth in energy use, to substantially reduce absolute US energy use, we need actual declines in energy use and hence must redouble our efforts. In the next sections, we discuss which actual energy use declines might be feasible.

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[1] See United States of America 2015.

[2] EIA is an independent agency housed within the US Department of Energy.

[3] Quadrillion is 1,000 trillion—that is, a 1 followed by 15 zeros. Typical medium-sized states such as Alabama, Minnesota, Missouri, Tennessee, and Washington use about two quads per year.

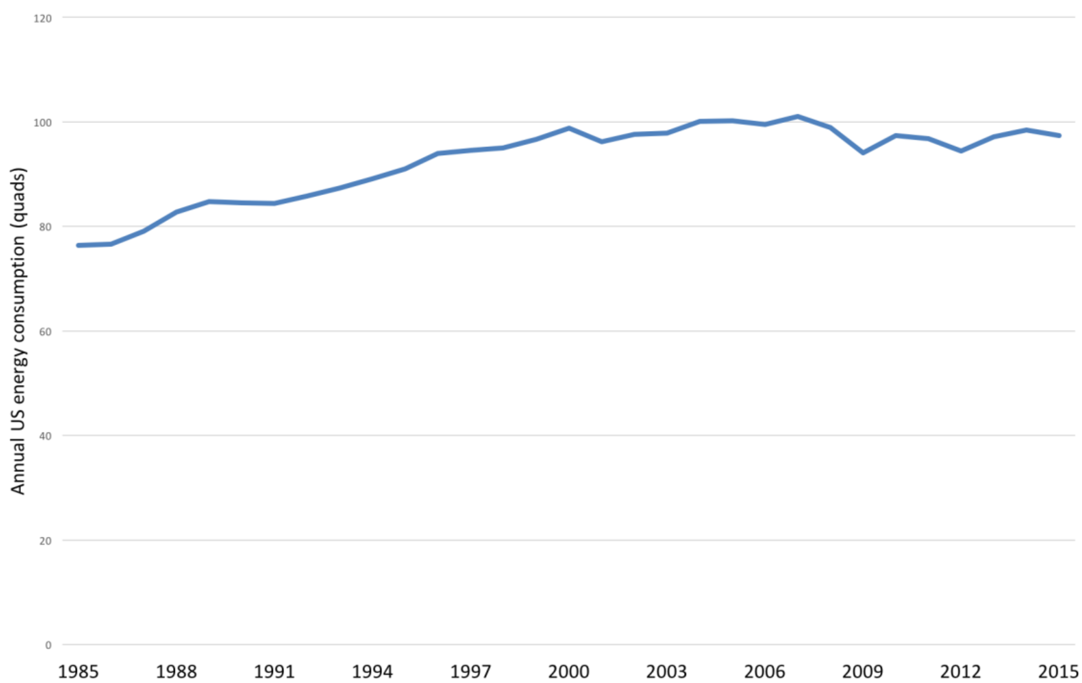

Figure 1. US annual energy consumption over 30 years, 1985–2015. *Source:* EIA 2016b.

Methodology for the New Analysis

Analytical Approach

Our approach was to compare the reference case in the *2016 Annual Energy Outlook* (2016 AEO) (EIA 2016a) to an energy efficiency case we prepared that estimated the energy savings from 13 packages of energy efficiency measures. We discuss key details of our analysis below and in Appendix A.

Reference Case

We used the 2016 AEO as our foundation for this new report, which provides a detailed forecast of US energy use out to 2040. Because the 2016 AEO extends out to 2040, we chose the same timeframe for our analysis. In the Results section, we discuss implications of this 2040 analysis for energy savings and use in 2050.

We use trends in the AEO from 2035 to 2040 to project total US energy use out to 2050, and we use this projection to assess what it would take to be on a pathway to achieve a 50% reduction in this usage by 2050. While we could extrapolate all parameters out to 2050, we decided not to for two reasons. First, these results would be subject to substantial uncertainty, since our simple extrapolations would be much less sophisticated than the detailed EIA models.[4] Second, much will change between now and 2040, and thus the actual

[4] EIA has indicated that the 2017 AEO will project out to 2050, making analyses out to 2050 more feasible in the future.

savings opportunities in the 2040–2050 decade will be substantially different from anything we might predict today.

While we generally used the 2016 AEO, we did make one adjustment. To derive primary energy use, the AEO generally calculates how much energy was used to generate electric power from renewable sources at the average heat rate for fossil-fuel power plants, 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 steadily over the 2017–2040 period. Therefore we adjusted the AEO to value power from renewable energy at the heat content of the electricity generated, which is 3,412 Btus per kWh of electricity.[5] On the other hand, we considered, but did not adjust for, energy efficiency already included in the AEO. 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. We could have added these savings into our base and then included these savings into our analysis, but decided it would be overly complicated and would not change the results very much.[6]

ENERGY EFFICIENCY CASE

To assess the potential impact of energy efficiency on economy-wide energy use in the United States, we looked at packages of energy efficiency technologies, policies, and programs that are targeted at specific end-use sectors. We estimated the energy savings of each package based on current research findings and ACEEE expert judgment. For each package, we looked at the base energy use in 2040 that would be affected (as projected in the AEO), how much each package could reduce this 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 small project we did not do a specific economic analysis. For some measures, the percentage savings applies to only a portion of use, but for others, the percentage reduction is an average reduction that applies to 100% of the use (while recognizing that some users will save more than the average and some will save less). Some overlap exists between measures, so we made a variety of adjustments to eliminate it. For example, many of the measures reduce electricity use, so we needed to adjust savings from improved power plant heat rates downward to account for the reduced need for power.

For our analysis, we looked at 13 energy efficiency measure packages:

- Appliance and equipment efficiency
- Zero net energy (ZNE) new buildings and homes
- Smart buildings and homes
- Home and building retrofits

[5] 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.

[6] We did conduct a side analysis making this adjustment, which is discussed in the Other Scenarios section of this report.

- Behavior change in buildings
- Industrial efficiency improvements
- Combined heat and power (CHP) systems
- Light and heavy duty vehicle fuel economy improvements
- Reductions in passenger vehicle miles traveled (VMT)
- Reductions in freight transport energy use
- Aviation efficiency improvements
- Conservation voltage reduction and reductions in losses from transmission and distribution systems
- Reductions in power plant heat rates

OTHER CONSIDERATIONS

Our analysis also includes consideration of both direct and indirect rebound effects. Direct rebound is the impact of purchasing an efficient product on the purchaser's use of that product. For example, a homeowner with an efficient air conditioner might run that air conditioner longer than a less efficient model. Indirect rebound reflects upstream impacts, such as the impact of respending money saved on energy bills; some of this respending might increase energy use. For most measures, we reduced energy savings by 10% to account for direct rebound (5% for the commercial sector, vehicles, and aviation). In addition, we reduced our overall savings by an additional 10% to account for indirect rebound. These figures are for the United States and are based on a recent paper reviewing many previous studies on the rebound effect (Nadel 2016b).

Efficiency Measure Packages

As discussed above, our analysis examined a baker's dozen of energy efficiency measures or sets of measures. Here, we discuss each of these packages, including what was in them, key assumptions, and steps that might be needed to realize the savings from each.

APPLIANCE AND EQUIPMENT EFFICIENCY

Federal minimum energy efficiency standards currently affect more than 50 types of appliances and equipment, ranging from residential refrigerators to industrial pumps. The US Department of Energy (DOE) estimates that standards already established will, on a cumulative basis, save more than 130 quads of energy through 2030, reducing energy bills by nearly $2 trillion (DOE 2016b). A recent report (deLaski et al. 2016) estimates savings for the next set of standards, covering those that will be set and take effect over the 2017–2029 period. This report estimates annual savings in 2035 and 2050, and we linearly interpolate 2040 savings. We add an allowance for additional standards set in the 2030–2040 period (discussed in Appendix A), and deduct 10% for direct rebound effects. This analysis might be conservative, as it does not include savings from more systems-based performance standards (e.g., those that look at entire HVAC systems, rather than individual components) and it does not include savings opportunities enabled by improved test procedures.

Our savings estimates involve standards on dozens of products, with 70% of the savings due to 10 products (residential water heaters, central air conditioners/heat pumps, showerheads, clothes dryers, refrigerators, and faucets, as well as commercial/industrial fans, electric motors, transformers, and air compressors). Achievement of the full savings potential for new standards will require various steps, including improved test procedures on some products (so that tests approximate performance in the field); 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, a rulemaking by DOE to adopt new standards that require increased but cost-effective levels of efficiency.

In addition to minimum efficiency standards, the efficiency of new equipment purchases is affected by voluntary equipment specifications such as ENERGY STAR. For example, ENERGY STAR has specifications on more than 50 different products, some of which are also covered by minimum efficiency standards and some of which are not. 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. To estimate the additional savings from ENERGY STAR, we looked at annual savings data for minimum efficiency standards and ENERGY STAR over the 2005–2015 period and calculated a ratio.[7] Over these 11 years, average ENERGY STAR savings were 34% of the savings from minimum efficiency standards; we therefore multiplied savings from standards by 1.34 to also include ENERGY STAR's impact.

ZERO NET ENERGY NEW BUILDINGS AND HOMES

Hundreds of new homes and commercial buildings have been built that produce at least as much energy as they use on an annual basis. Commonly labeled *zero net energy* (ZNE) buildings, 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 ZNE are ultra-low energy (ULE) buildings. By reducing energy use, ULE construction makes ZNE much more feasible and is sometimes labeled "ZNE ready." The New Buildings Institute has documented 394 commercial buildings in the United States that, as of September 2016, are either verified ZNE, not-yet-verified ZNE, or ULE (NBI 2016). The Net-Zero Energy Coalition has identified more than 3,000 ZNE or ZNE-ready homes and residential buildings in the United States that collectively contain more than 6,000 housing units (NZEC 2016). Several efforts are targeting the adoption of ZNE codes by around 2030; for example, such targets are envisioned by the state of California and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (CPUC 2011; ASHRAE 2008).

For our savings estimate, we assume that ZNE performance is required in building codes applying to 80% of new construction in 2031 and beyond. For these buildings, we assume 80% energy savings relative to reference case efficiency levels for new construction (with the other 20% coming from on-site renewable energy systems). The other 20% of construction is either in states without such codes or in building types, such as hospitals, where energy intensities are high and ZNE performance is probably not possible. For residential and commercial new construction in 2030 and before, we use the new construction savings estimates developed by York et al. (2015a). Because most of the savings are from ZNE

[7] Appliance standards savings came from an unpublished spreadsheet provided by J. Mauer, Appliance Standards Awareness project (sent to S. Nadel on March 13, 2015). ENERGY STAR savings came from an unpublished spreadsheet provided by K. Vokes of the EPA (sent to S. Nadel on October 25, 2016).

buildings (e.g., all buildings after 2030 plus a substantial number of ZNE buildings in earlier years), renewable energy systems should be sized to cover any rebound effects.

Amann (2014) discusses obstacles to the goal of widespread ZNE use by 2030 and suggests a combination of R&D, implementation, and building code strategies for reaching the target. For example, R&D needs include development of workable system performance metrics and 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, green codes, and beyond-code guidelines and incentives[8]; and valuing efficiency in financial transactions.[9] 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.

SMART BUILDINGS AND HOMES

One large class of system improvements has been labeled *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 system parameters and finds ways to improve system operation after learning a household's patterns (e.g., when people are home and which temperatures they like). In homes, average heating and cooling savings of around 12% have been documented (York et al. 2015a). We estimate that 80% of homes could have learning thermostats or another analogous control system[10] by 2040. We also estimate that additional home energy management controls can save half this amount (6%) in other end uses, representing an additional 30% of residential energy use (Dobush 2015). More sophisticated systems used in commercial and industrial buildings offer even greater reductions in energy use. Rogers et al. (2013) estimate a 28% average savings available in commercial buildings (weighted average across all end uses). They also estimate a 50% market penetration for intelligent efficiency by 2035; we round up to 60% by 2040. As discussed in the methodology section, we estimate that direct rebound will reduce residential savings by 10% and commercial savings by 5%.

Rogers et al. (2013) also 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

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[8] *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.

[9] For example, including efficiency features in building appraisals and considering both energy and mortgage costs in mortgage underwriting decisions.

[10] For multifamily buildings with central heating systems, for example, other controls will be needed.

capabilities and benefits; documenting best practices from early projects; and demonstrating projects in promising market niches that lack documented results.

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. Programs such as Home Performance with ENERGY STAR can reduce energy use by 20–30% (for example, see Belzer et al. 2007), 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 is projected to reduce energy use by 38% (Harrington and Carmichael 2009), while a deep energy retrofit of a large federal office building in New Carrolton, Maryland, is projected to reduce energy use by 60% (GSA 2014).[11] However participation in retrofit programs is generally low. For example, Neme et al. (2011) and York et al. (2015b) found that the highest participation rates for comprehensive retrofit programs across broad numbers of customers approached but did not reach 2% of those eligible each year. Some geographically targeted or single measure programs had higher participation rates and could 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, let alone the New Carrolton building.

For our savings estimate, we assume 30% on average. These savings are applied after subtracting savings from measures discussed in prior sections, thereby avoiding double counting of savings. For homes, we estimate 50% of homes can be retrofit (about 2% per year). For commercial buildings, we estimate 75% of floor area can be retrofit, as owners will periodically update large buildings to retain their market position.[12] We reduce these savings estimates to account for direct rebound (10% in homes, 5% in commercial buildings).

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, rating, 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, and improved program designs to increase participation rates and savings per home (Cluett and Amman [2016] discuss a variety of promising strategies). In addition, some mandatory policies might be needed, such as building retrofit ordinances. For example, France recently passed a law requiring existing homes to meet steadily more stringent energy efficiency requirements, with the targets set many years in advance. In Europe, many buildings are rated on an A–G scale, with A being the most energy efficient.

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[11] Most of the savings are from energy efficiency improvements, but the 60% savings estimate also includes a solar system.

[12] Alternatively, the same savings would be achieved by deep retrofits in 45% of buildings that save an average of 50%.

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, where first E, then D, C, and B might be required.[13] Implementing regulations for the early tiers still must be developed, while the latter goals do not yet have the force of law. In the United States, New York City has a regulation in place mandating that lighting systems in existing buildings be upgraded by 2025 (City of New York 2009).

BEHAVIOR CHANGE IN BUILDINGS

Influencing the decisions people make in how they use energy can also achieve substantial savings. For example, Sussman and Chikumbo (2016) looked at various programs aimed at promoting behavior change in buildings and found savings of 0.5–23%, depending on the program. Shui (2012) found approximately 4–5% average energy savings from several efforts to encourage employees in hospitals and government buildings to use energy more efficiently. Foster and Mazur-Stommen (2012) found 4% average savings from providing real-time feedback to households about their energy use and offering information to help interpret and manage the usage numbers. And Grossberg et al. (2015) found savings of 3–6% in large-scale uses of games and competitions designed to encourage reduced energy consumption.

Combining these and other opportunities, researchers have published several estimates of total potential savings from behavior change programs. A recent DOE review of a dozen of these estimates showed that behavior change could result in potential savings of 0.3–15%, with a median savings of 6% (Navigant, 2016). We reduced our estimate of average savings to 4% (an educated guess) because we focus on achievable rather than technically possible savings, and we exclude the savings from transportation-related behaviors, home investment behaviors, embedded energy (i.e., energy used to produce and distribute consumer goods), and intelligent efficiency that are covered in other sections of this report. Behavior change savings estimates were generally determined by looking at actual energy use for a sample of participants and thus already factor in any direct rebound that occurs.

Achieving these savings will require work with many homes and commercial buildings. One approach is to send out home energy reports, which are regular mailings informing residents of their energy use relative to similar others and how they can reduce their consumption. Large-scale applications of this type of report among residential consumers enrolled by default reduce energy use by 0.5–2% depending on the fuel and application (Sussman and Chikumbo 2016). We will need to combine these programs with other residential and commercial strategies to further increase savings.

Additional programs might include real-time feedback (e.g., using in-home displays or workplace dashboards), competitions and games (at work or home), community-based programs (in buildings, neighborhoods, businesses, or cities), and school education programs. Each of these has the potential to further reduce energy consumption in buildings

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

but, unlike home energy reports, they require participants to actively enroll to participate (they cannot be enrolled by default). Therefore, in addition to research on how these programs can be improved, future research should focus on how to increase enrollment. Sussman and Chikumbo (2016) discuss results of some already completed programs and experiments, as well as other ideas worth exploring.

INDUSTRIAL EFFICIENCY IMPROVEMENTS

The industrial sector has been steadily improving in energy intensity.[14] Industrial energy use per dollar of shipment value declined 38% over the 1980–2013 period (Nadel, Elliott, and Langer 2015), which is a compound average annual decline of about 1% per year. EIA projects that over the 2015–2040 period, this metric will decline by 0.8% per year (EIA 2016a). These reductions in energy intensity result from changes in the processes used to produce goods, optimization of these processes (often involving learning by doing), and shifts in the mix of products we produce.

Given global pressures to reduce GHG emissions and compete internationally, we think more rapid intensity improvements can be achieved. We therefore estimate improvements of 1% per year beyond what EIA projects—similar to projections made by Laitner et al. (2012) and Lovins and Rocky Mountain Institute (2011). This estimate already incorporates any direct rebound effects.

To achieve these savings, improvements must be made in industrial processes, such as when facilities are periodically modernized, including taking advantage of research and development advances. Sometimes the savings are small; other times they can be dramatic. An example of the latter is submerged combustion melting, which can reduce energy use for melting glass and metal by 20–50%, depending on the application (Purnode 2008).

We also anticipate that smart manufacturing (applying intelligent efficiency strategies in the industrial sector) will contribute significantly to these intensity reductions, as will optimization of the motor, fan, pump, and compressed air systems that are widely used in industrial facilities. 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.

As discussed in Laitner et al. (2012), other major opportunities for reducing industrial energy intensity include changes in feedstocks and shifting to less energy intense materials. One important opportunity identified in the 2012 report was a shift to a full lifecycle approach to products, in which materials are recycled into feedstocks to produce new products, thus reducing the embedded energy in the products. And finally, industrial energy efficiency can be advanced by promoting and implementing continual improvement processes—often labeled *strategic energy management*—such as the ISO-50001 or DOE Superior Energy Performance (incorporated into their Better Buildings, Better Plants

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[14] For the industrial sector, we use energy intensity rather than energy efficiency, since industrial output varies significantly year to year as economic forces change.

program) (for more on this, see the "Strategic Energy Management" chapter in York et al. 2015a).

COMBINED HEAT AND POWER SYSTEMS

CHP, also referred to as *cogeneration*, is an energy-efficient method of generating both electricity and useful thermal energy in a single, integrated system. A CHP system saves energy by recovering heat that would otherwise be wasted from power-only generation and using it to satisfy on-site thermal energy needs. The United States presently has about 80,000 MW of CHP generating capacity (Nadel et al. 2015). Based on a state-by-state analysis prepared for DOE (2016a), we estimate that about 47,000 additional MW of capacity are available, with a return on investment of 10% per year or more. We estimate that 80% of this capacity could be built by 2040, and that on average this new capacity would operate for 4,437 hours per year (Kelly 2016).

Developing this capacity will require experienced companies to engineer, finance, operate, and maintain these systems. While some large industrial and institutional customers—and a few private engineering firms—can do this, many cannot. Another option is for electric and gas utilities to build, own, and operate CHP as regulated assets, as is the case with utilities in Alabama, Florida, North Carolina, and Texas (Chittum 2013 and 2016). In addition, there need to be reasonable interconnection requirements with the local utility, and reasonable tariffs in place for the sale of excess power to the utility and the purchase of needed backup power from the utility. Output-based emissions regulations (emissions limits per kWh produced) for CHP systems would also help; such regulations reward very high-efficiency systems relative to traditional input-based emissions regulations, which look only at the amount of fuel burned, regardless of the system's efficiency.[15]

LIGHT AND HEAVY DUTY VEHICLE FUEL ECONOMY STANDARDS

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). Current standards are expected to yield an average fuel economy of 46.3 miles per gallon (mpg) for new vehicles in 2025 as measured in laboratory test procedures (EPA and NHTSA 2016b); this equates to about 37 mpg in on-road operation. For our estimates, we assume that continued improvements in fuel economy of petroleum-powered vehicles, as well as growth in the market share of electric vehicles (which are generally more efficient than gasoline vehicles), will increase average light duty vehicle mpg to 70 mpg in 2040 (as measured in the test lab).[16]

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 vehicles can be much lighter if crashes are not a concern. On the other hand, investigations of autonomous vehicle scenarios to date point out the various ways their emergence could

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[15] These and other implementation issues are discussed more fully at aceee.org/sector/state-policy/toolkit/chp.

[16] The 70 mpg figure does not reflect energy use at power plants needed to generate the electricity used to charge electric vehicles. We do, however, incorporate this extra electricity use in the details of our analysis.

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

Likewise, EISA 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 vehicle fuel use is projected to decrease by an average of 37% by 2027, relative to 2010 vehicles (Khan 2016). For our estimate, we project a 29% reduction in new vehicle fuel use by 2040 beyond the levels in the AEO. This includes savings from the second phase of heavy duty truck standards, plus an additional 1% per year improvement in new trucks in the 2027–2040 period not yet covered by standards.

Based on published estimates, we incorporate 5% direct rebound for light vehicles and heavy vehicles (Nadel 2016a; EPA and NHTSA 2016a).

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[17]) and expanded efforts to promote and incent high-efficiency vehicles including hybrid, plug-in hybrid, and all-electric vehicles.

REDUCTIONS IN PASSENGER VEHICLE MILES TRAVELED

New mobility options, especially in urban areas, could reduce many people's need to drive or own personal vehicles over time. These options include ridesharing, carsharing, and real-time transit information. 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 bike-friendly streets, residents will rely on non-motorized modes to meet more of their work and non-work mobility needs. On-demand vehicle access that is reliable and affordable will allow many households to forego vehicle ownership altogether. These changes to the built environment should permit a substantial decline in VMT overall. Such a result is not guaranteed, however, especially if these mobility services instead replace public transit and provide single-occupant vehicle services to children and others who do not currently drive.

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) estimated a potential 13% reduction in light duty fuel use by 2030 from six strategies based on ICTs, including carsharing, real-time transit information, and vehicle-to-vehicle communications. Based on these estimates, for our savings calculations, we estimate that VMT can be reduced by 20%

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[17] For more information on the SuperTruck program see energy.gov/sites/prod/files/2016/06/f32/Adoption%20of%20New%20Fuel%20Efficient%20Technologies%20from%20SuperTruck%20-%206-22-16%20%28002%29.pdf.

in 2040 relative to the 2016 AEO reference case. This estimate includes direct rebound effects.

The 2016 AEO projects an average annual VMT growth of 0.9% from 2015 to 2040, which is slightly higher than population growth (0.7% per year). Achieving a 20% reduction in VMT by 2040 relative to this projection would require an average *reduction* in VMT per capita of 0.6% per year. US urban population is more than 80% of total population, and that percentage is growing (Census Bureau 2012); we assume that VMT reduction strategies affect primarily this population. Consequently, urban residents would need to reduce their VMT per capita by about 1% per year to achieve the requisite overall reduction.

Implementation of California's SB 375, the *Sustainable Communities and Climate Protection Act of 2008*, provides some insight into how such reductions might be achieved. Pursuant to SB 375, Metropolitan Planning Organizations (MPOs) covering 95% of the state's population adopted plans in 2011 to reduce VMT per capita from 2005 levels by 10–16% in 2035 (ARB 2014). The primary mechanism for achieving SB 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.

No similar policy framework currently exists at the federal level. However the US Department of Transportation (DOT) solicited comments in its third proposed performance management rule on whether DOT should require federal transportation funding recipients—including State DOTs and MPOs—to set targets for mobile source GHG emissions in the future and measure performance toward meeting those targets.[18] Establishing such targets would help achieve the substantial VMT reductions we model.

Reductions in Freight Transport Energy Use

Apart from improving the fuel efficiency of individual trucks, highway freight transport can increase energy efficiency through a variety of techniques. For example, freight energy use can be reduced by reducing empty backhauls and increasing the truck load factor in general, such as through collaborative shipping arrangements. Such strategies can draw on growing applications of ICTs 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' fuel consumption by 4% on average (Trucking Efficiency 2014).

The ability to automatically track and handle goods and predict freight vehicle movements has major implications across the freight system. 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 assigning loads to the least energy-intensive mode that meets each load's needs.

[18] 81 Fed. Reg. (no. 78, April 22, 2016).

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, not including vehicle efficiency technology gains. Based on this analysis, we assume 20% freight system energy reductions by 2040 in our analysis (including direct rebound).

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, such as by

- 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

AVIATION EFFICIENCY IMPROVEMENTS

Aviation accounts for nearly 3% of projected 2040 energy use. Furthermore, energy use for aviation is projected to grow more rapidly than all other transportation segments, as well as most non-transportation segments (EIA 2016a). Greene and Plotkin (2011) examined opportunities to reduce aviation energy use including improved engines and airframes, operational efficiency, and changes in travel. Their mid-case estimate is 32% savings in 2035 and 56% savings in 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). For our analysis, we use the Greene and Plotkin estimates, interpolating 40% savings in 2040. We could not find any published estimates on direct rebound in the aviation sector, so absent other data, we assume 5% rebound.

Energy use per revenue seat mile declined by nearly 50% from 1980 to 2012 (Nadel et al. 2015). These trends are likely to continue for several reasons. 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. Further, 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 2017 (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 and may move forward with aircraft emissions standards (EPA 2016); such standards would likely go beyond the ICAO agreement. Absent such standards, the European Union's inclusion of GHG emissions in its Emissions Trading Scheme in all likelihood will be applied to European routes of US airlines.

Conservation Voltage Reduction and Reductions in Losses from Transmission and Distribution Systems

In the United States, about 6% of electricity generated is lost during the transmission and distribution (T&D) of power.[19] Additional energy is lost from electric wires in homes, buildings, and factories. At the grid level, these losses can be reduced through lower-loss wires and transformers, as well as improved control of voltage and other power parameters. Also, greater use of distributed generation can reduce grid losses as power can often be generated closer to the load (grid losses depend in part on the distance that power is transmitted). In homes and buildings, these losses can be reduced by improved voltage control on utility circuits, reducing the overvoltage through a measure often called *conservation voltage reduction* (CVR).

T&D losses average about 4% in Germany and about 4.5% in Japan (World Bank 2014). While these countries are more compact than the United States, with improved controls and other technologies—as well as increased use of distributed generation—we estimate that the United States can, by 2040, reduce T&D losses to Japan's level, saving 1.5%. In addition, CVR can be employed, using sensors at the ends of distribution feeders to sense actual voltage, and then reducing voltage to the minimum required levels. York et al. (2015a) summarize eight different studies on the resulting savings, finding average savings of 2.3%. We add together the 1.5% T&D savings and the 2.3% CVR savings for our savings estimate. Also, volt-VAR grid-edge optimization techniques are now reaching the market, which on some circuits have demonstrated up to 2% additional CVR savings (Moghe et al. 2016). We do not include these in our savings calculations, preferring to see data on more circuits, but such techniques can potentially provide either additional savings or make up some of the lost savings if our estimate of 1.5% T&D savings proves too ambitious.

Multiple utilities are now implementing CVR (York et al. 2015a), and the number is growing every year. 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 manor. Utilities are also gradually improving their T&D systems—losses were more than 7% as recently as 2002 (Nadel et al. 2015). Smart grid efforts and intelligent grid optimization might continue these trends. Utility regulators should keep an eye on trends; if losses do not decline at the rate needed, they can take additional actions to encourage or require implementation of CVR and T&D loss reduction programs.

[19] www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

REDUCTIONS IN POWER PLANT HEAT RATES

Heat rate is a measure of how much fuel a generating station must burn to produce a kWh of electricity. In the United States, average heat rates have gradually declined as new, more efficient plants are built, existing plants are improved, and old inefficient plants are retired. In 1990, the average US heat rate was 10,402 Btus per kWh; in 2013, it was 9,541 (Nadel et al. 2015). Much better heat rates are possible. For example, advanced natural gas fired combined cycle power plants can achieve average heat rates approaching 6,000 Btus per kWh (Nadel 2016a), reducing fuel use by more than one-third relative to fuel use at the average plant in operation today. More efficient coal plants are also possible, with the best heat rates under 9,000 Btus per hour (Williams 2014). And, as discussed in the Methodology section, most renewable energy systems do not burn fuel, so we value their energy use at 3,412 Btus per kWh; under this assumption, as renewable energy penetration increases, heat rates will improve.

On the other hand, not all new plants will be efficient. Simple peaking plants that operate only a few hundred hours per year can have heat rates above 12,000, and as renewable energy generation increases, these peaking plants might be used more often to help manage loads. In addition, in some regions, water for cooling is in tight supply. Hybrid-dry cooling can be used, but these systems increase heat rates. Still, these higher heat rate systems are likely to be limited in number or hours of use. Overall, we estimate that, by 2040, the average natural gas and coal plant can have a heat rate midway between the 2014 average and the best actual heat rate today, with more modest improvements in nuclear plant heat rates. For our savings calculations, we use heat rates of 3,412 for renewables, 7,034 for natural gas, 9,643 for coal, and 10,000 for nuclear.[20] With these assumptions, the weighted average heat rate is 6,965 in 2040—a 5.6% reduction from the 8,908 we derived for 2040 from the 2016 AEO.[21] Also, the AEO projections of renewable energy shares may be conservative; if more renewable energy systems are deployed, heat rate will decline below the values we show here, either adding additional savings or making up some savings if any of the above estimates prove too ambitious.[22]

Achieving these savings will require both upgrades to existing power plants and replacement of inefficient power plants with new, much more efficient ones. Retirement of old, inefficient plants is being spurred by emissions regulations for various pollutants. When new plants are built, only the most efficient plants for the chosen fuel should be constructed. EPA carbon dioxide (CO_2) emissions regulations for new sources will influence these choices, as will state utility and air regulators.

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[20] This is down slightly from the US nuclear plant average of 10,459 in 2014 (www.eia.gov/electricity/annual/html/epa_08_01.html).

[21] This 8,908 figure was calculated using 3,412 Btus/kWh for renewable energy.

[22] Such a scenario is discussed in the Other Scenarios section of this report.

OTHER MEASURES

In addition to the energy-saving measures described above, there are many other opportunities to reduce energy use that we did not analyze. Examples include opportunities to reduce energy use by boats, trains, buses, and many types of miscellaneous equipment in the residential and commercial sectors (ranging from elevators to gas pumps[23]). Also, this report does not examine opportunities to save energy by fuel switching in the residential, commercial, and industrial sectors.

Analysis Results

ENERGY SAVINGS

Our analysis considers how much energy can be saved in 2040, and whether these savings put us on a path to cut projected US energy use in half by 2050. We find that, taken together, the energy efficiency measures we examined would reduce 2040 energy use by 34%, bringing 2040 energy use down to 66 quads, and approximately putting us on a path to achieve the 50% energy savings goal.

Specifically, EIA projects that energy use will be 107 quads of energy in 2040. If we value renewable electricity at 3,412 Btus/kWh (as discussed in the Methodology section), this reduces projected 2040 energy use to 100 quads. Extrapolating forward to 2050 (based on trends in the 2035–2040 period), results in the reference case energy demand increasing to 108 quads in 2050. Thus, a 50% reduction by 2050 would mean cutting this to 54 quads. To be on a straight-line trend to hit this 2050 target, we will need to use 65 quads in 2040. Our analysis finds that achieving 66 quads in 2040 is feasible if we combine the various measures discussed in the prior section, eliminating overlap between measures and including direct and indirect rebound effects. Thus, we are one quad off in our primary analysis. As discussed below, our other scenarios show additional savings. Results of our primary analysis are shown in figure 2, and further details are provided in Appendix A.

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[23] A few of the equipment efficiency standards and ENERGY STAR specifications affect miscellaneous energy uses; these uses are addressed in zero net energy buildings and, to a limited extent, by behavioral programs, but most miscellaneous use is not addressed in our analysis.

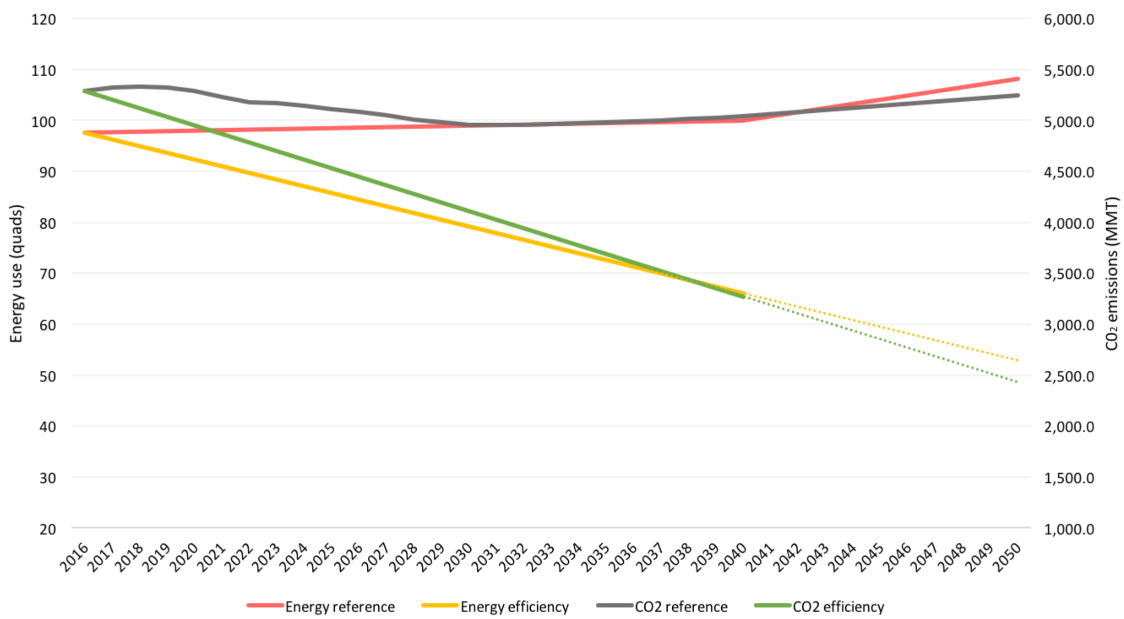

Figure 2. Energy use and carbon dioxide (CO_2) emissions in the reference and efficiency cases

EMISSIONS REDUCTIONS

We also looked at carbon dioxide (CO_2) emissions in the reference and efficiency cases. The 2016 AEO provides the reference case CO_2 emissions (EIA 2016a). Efficiency case emissions are based on energy use for each fuel and average emissions rates for each as estimated by EIA. Details of the assumptions and analysis are in Appendix A, and figure 1 shows the results of the analysis. In the efficiency case, 2040 CO_2 emissions are reduced by 35% relative to the 2040 reference case, also putting carbon emissions on a 50% reduction path. The United States and many other countries are targeting GHG emissions reductions of 80% or more relative to 2005 levels. For the United States, emissions in our 2040 efficiency case are 45% below 2005 levels. Additional emissions reductions will be needed to reach the 80% reduction goal, including additional efficiency savings in the 2040–2050 period, as well as additional non-efficiency measures, such as increased use of zero-emissions energy sources (e.g., renewable and nuclear energy), possible use of carbon capture and storage techniques, and reductions in GHGs besides CO_2 (e.g., methane and halons).

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 to double energy productivity by 2030 relative to a present-day base (Rhodium Group 2013, DOE 2015). *Energy productivity* is a measure of the amount of gross domestic product (GDP) that is generated on average per unit of energy consumption. For example, the 2016 AEO predicts an energy productivity for 2016 of $175 billion per quad of energy use.[24] In the AEO reference case for 2040, this increases 62% to $284 billion per quad. And, in our efficiency case for 2040, energy productivity is increased by a factor of 2.5 relative to 2016 levels, increasing to $430 billion per quad.[25] Energy productivity more than doubles in our efficiency case, while energy use declines only 34% because GDP is expected to grow substantially in the coming decades (up 69% in inflation-adjusted dollars, according to the 2016 AEO). 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 sectors—residential, commercial, industrial, transportation, and power. Savings and emissions reductions are largest in the transportation sector, followed by the commercial, industrial, and residential sectors. Savings are smallest in the power sector because its savings are from efficiency alone—the emissions reductions will increase substantially if zero emissions electric generation (e.g., renewable and nuclear energy) become more common by 2040 than EIA estimates. Transportation measures generally contribute a higher percentage to emissions reductions than to energy use reductions due to the relatively high carbon content of most transportation fuels. These proportions are shown in figures 3 and 4.

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[24] This figure is with renewable electricity valued at 3,412 Btus/kWh.

[25] 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 increase energy productivity a little higher than what we show here.

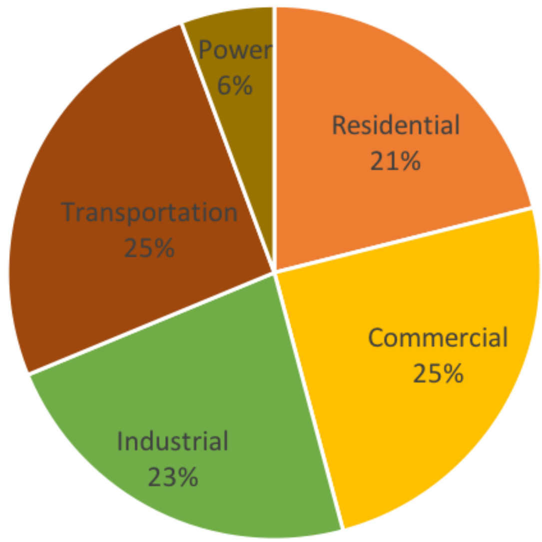

Figure 3. Allocation of energy savings among sectors

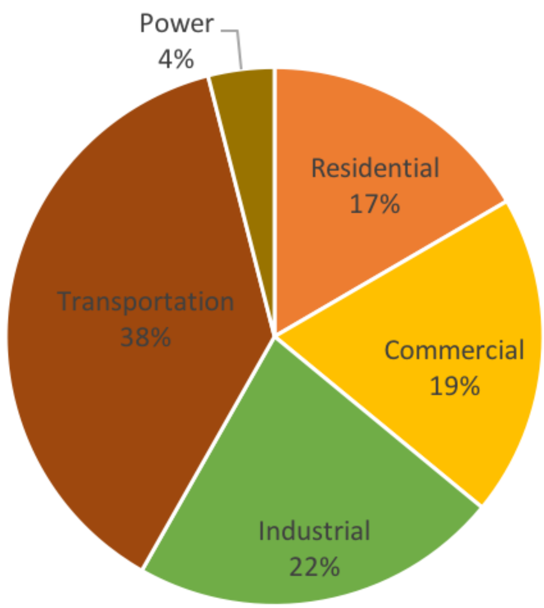

Figure 4. Allocation of CO_2 savings among sectors

SAVINGS BY MEASURE

Each of the 13 measures we examined contributes to putting us on the 50% energy use reduction path. The largest savings come from the industrial efficiency package, followed by ZNE new homes and buildings, vehicle fuel economy improvements, appliance and equipment efficiency, and home and commercial building retrofits. Figure 5 shows the proportion of the total energy use reduction for each measure, while figure 6 shows the allocation of emissions reductions by measure. In general, the percentage reductions for each measure are similar in figures 5 and 6 except for vehicle fuel economy, which contributes disproportionately to emissions reductions. This is due to the relatively high carbon content of gasoline and diesel fuel; also, our fuel economy measure includes greater use of high-efficiency electric vehicles, which have lower emissions than gasoline vehicles given the 2040 electric generation mix projected in the 2016 AEO and used in our efficiency scenario. Other transportation measures also generally contribute a higher percentage to emissions reductions than to energy use reductions due to the relatively high carbon content of most transportation fuels. On the other hand, for homes and buildings, energy use percentage reductions are generally greater than CO_2 reductions because a substantial portion of residential energy comes from natural gas, which is a relatively clean fuel.

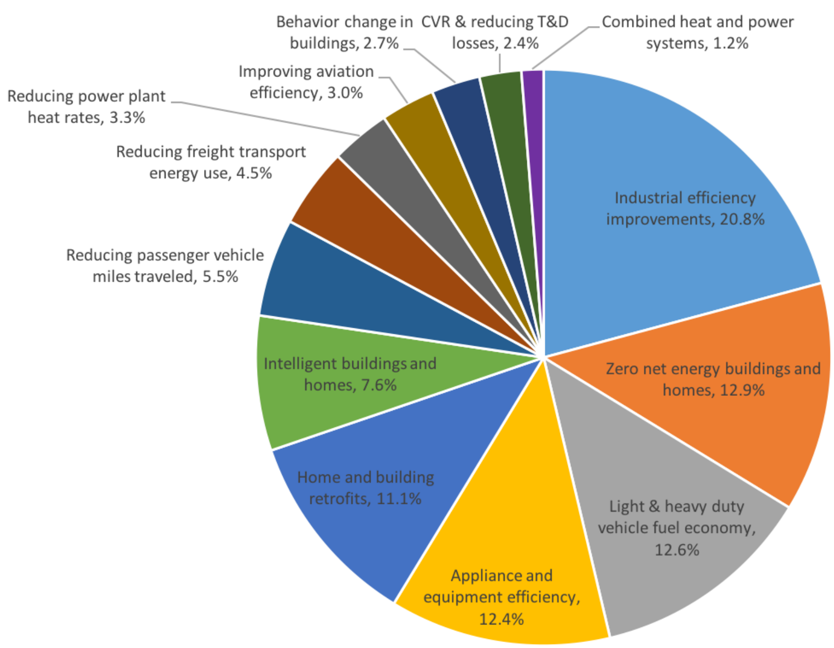

Figure 5. Allocation of energy savings among measures

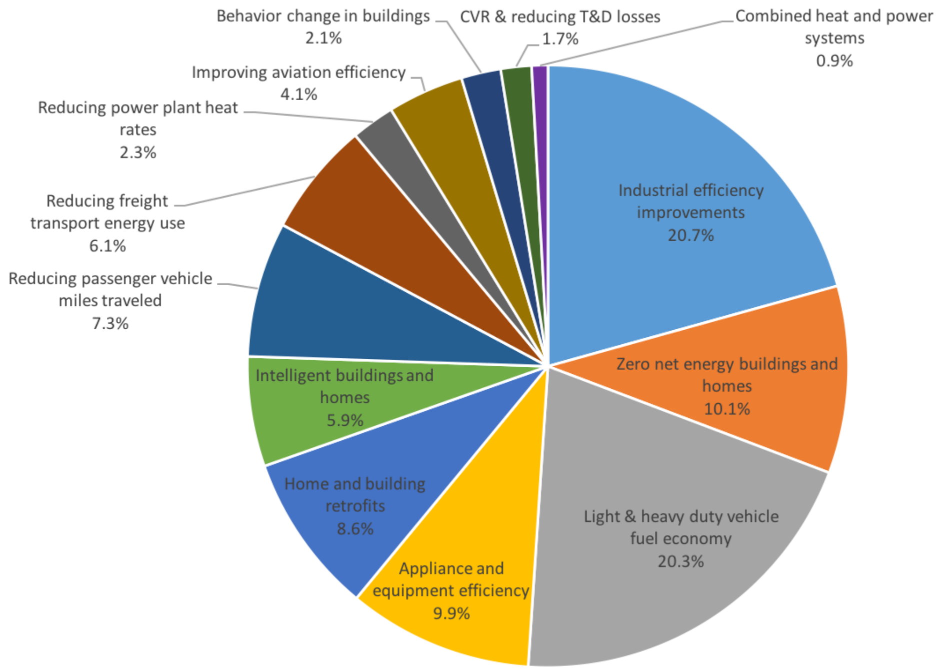

Figure 6. Allocation of CO_2 savings among measures

OTHER SCENARIOS

Greater Use of Renewable Energy

Some analysts have questioned whether EIA is overly conservative in its projections of future penetration of renewable energy for electricity generation (e.g., Rogers 2015). To address this concern, we ran a scenario that assumed that by 2040, half of US electricity would come from renewable energy, one-quarter from gas, and one-quarter split evenly between coal and nuclear. Several states have set high targets for electricity generation from renewables, including California and New York (both 50% renewables by 2030), Vermont (75% by 2032), and Hawaii (100% by 2045).[26] If a significant number of states follow suit, 50% renewables by 2040 will be feasible. In this scenario, due to the much higher renewable power (which is valued at 3,412 Btus per kWh), savings from the heat rate improvement measure increase to 7.0 quads (compared to 2.0 quads in the primary analysis), increasing overall 2040 energy savings to 38% of projected 2040 US energy use and overall carbon emissions reductions to 43% of projected 2040 US carbon dioxide emissions and 52% of 2005 carbon dioxide emissions. We decided not to use this scenario as our primary scenario because (1) greater use of renewable energy is not really an energy efficiency measure, and (2) there is substantial uncertainty as to whether 50% renewable electricity by 2040 is realistic. Still, it is useful to know that increased renewable energy use would have a substantial impact on both energy use and CO_2 emissions.

[26] See www.ncsl.org/research/energy/renewable-portfolio-standards.aspx, www.eia.gov/todayinenergy/detail.php?id=25932, and www.eia.gov/todayinenergy/detail.php?id=21852.

Savings Relative to 2011 AEO Baseline

This paper examines predicted 2040 and extrapolated 2050 energy use based on the 2016 AEO. As noted in the Introduction, an earlier ACEEE analysis (Laitner et al. 2012) used the 2011 AEO as a base. Using the 2011 AEO, estimated energy use for 2050 is 124 quads if renewable energy use is valued at the fossil fuel heat rate.[27] If we value renewable electricity at 3,412 Btus per kWh, the 2050 estimate derived from the 2011 AEO drops to 119.3 quads. Thus, a 50% reduction would target about 60 quads by 2050. Our new analysis projects 2050 reference case energy use to be 108.4 quads, a drop of more than 10 quads, indicating significant progress toward the 60 quad by the 2050 goal. We did not do a detailed comparison between the 2011 and 2016 AEOs, but significant efficiency improvements occurred between 2011 and 2016 (see Nadel et al. 2015). The 2016 AEO also projects a higher renewable electricity share, which, given our assumption of 3,412 Btus per kWh, affects the projected 2050 energy use (e.g., we extrapolate a 34% renewable electricity share in 2050 from the 2016 AEO, up from 15% in the 2011 AEO).

Looking forward, our analysis of potential efficiency savings finds that reducing 2040 energy use to 66 quads is feasible, approaching the earlier goal for 2050. Thus, with our earlier baseline and target, the 50% reduction energy use reduction goal will be easier to meet.

Energy Efficiency Already Included in the AEO

The 2016 AEO includes a variety of efficiency actions that will occur during the 2016–2040 period due to policies that were put in place in 2015 and earlier. For example, the 2016 AEO includes savings from appliance, equipment, and vehicle standards that affect the efficiency of products purchased over the 2016–2040 period. The AEO forecast also implicitly assumes that savings from state and utility energy efficiency programs will continue at historic levels. We looked at savings from two of these policies. First, the Appliance Standards Awareness Project (ASAP) maintains a model to estimate savings from current and possible future appliance and equipment standards. ASAP estimates that standards saved 6.06 quads in 2016 and that this figure will rise to 9.39 quads in 2040, including savings from all standards established by the end of 2015 (J. Mauer, ASAP, pers. comm., September 20, 2016). Thus savings of about 3.3 quads are included in the 2016 AEO (these are savings from appliance standards set before 2016 but that affect the efficiency of product sales in 2016 and beyond). Second, the AEO implicitly builds in an historic level of savings from state and utility efficiency programs. According to the ACEEE *2016 State Energy Efficiency Scorecard* (Berg et al. 2016), in the past five years, these programs have reduced US retail electric sales by about 0.67% per year. Molina (2014) estimates that the average program measure has a life of about 10 years. Thus, 10 years of 0.67% year of savings is about 2.2 quads[28] of 2040 savings included in the 2016 AEO.

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[27] The 2011 AEO ends in 2035, while the 2016 AEO ends in 2040. We project 2050 energy use by extending to 2050 the growth rate in the final five years of the AEO Reference Case scenario.

[28] 4,464 TWh of sales in 2040 from the 2016 AEO * 0.67% per year * 10 years /7,382 average 2040 heat rate (from the 2016 AEO, but valuing renewable electricity at 3,412 Btus/kWh).

If we were to include these savings in our analysis, the savings would be higher, but base case energy use would also be higher because savings from these policies would need to be added to the base case. Our primary analysis estimates 34% energy savings in 2040 from the efficiency measures we examined. If the base case and savings were both 5.5 quads higher (sum of standards and utility programs), these savings would increase to 37%.

Conclusions

Our analysis finds that the 13 efficiency measures we examine, if pursued aggressively, would reduce 2040 energy use by 34%, putting the United States on a path to reduce 2050 energy use by 50% relative to currently predicted levels. Achieving these energy efficiency savings will require expansion of energy efficiency efforts beyond business-as-usual, including

- New building codes, equipment efficiency standards, and ENERGY STAR specifications
- Substantial improvements to existing factories, homes, commercial buildings, T&D systems, and power plants
- Efforts to better manage freight and aviation energy use, reduce VMT, and spur changes in how individuals use energy at home, at work, and in transport

We must rigorously pursue all of these opportunities, particularly emphasizing those with the largest savings, as shown in figures 2 and 3—industrial efficiency improvements, ZNE buildings and homes, light and heavy duty vehicle fuel economy improvements, appliance and equipment efficiency efforts, and home and building retrofits.

We have examined savings through 2040, but to achieve the 2050 goal will require continuing efficiency efforts, including continuing the efforts profiled here for another decade, improving these efforts based on lessons learned over the 2016–2040 period, and pursuing new energy-saving opportunities that become apparent over the next two decades. We must also continue to invest in research and development to identify new efficiency measures; these measures will provide additional savings opportunities that we can only imagine today and that will complement the measures we examined. Through these steps, we can reduce energy use, reduce emissions, and strengthen our economy.

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Appendix A. Calculation Details

Table A1. Energy savings by measure

	2030				2040				
Measure	Base use	% Svgs	% Applies	Q Saved	Base use	% Svgs	% Applies	Rebound	Q Saved
Reference case				101.5	107.1				
with RE at 3412 Btu/kWh					99.9				
Appliance and equipment efficiency				1.26	NA			10%	4.7
ZNE new commercial buildings	4.1	40%	38%	0.6	3.2	80%	80%	included	2.7
ZNE new homes	2.8	37%	38%	0.4	2.7	80%	80%	included	2.1
Smart buildings					13.9	28%	60%	5%	2.2
Smart homes					12.9	12%	45%	10%	0.6
Residential retrofits					12.2	30%	50%	10%	1.7
Commercial building retrofits					11.7	30%	75%	5%	2.5
Behavior change in homes & buildings					25.6	4%	100%	included	1.0
Industrial efficiency improvements					37.8	21%	100%	included	7.8
CHP					NA			0%	0.5
Light-duty CAFÉ					11.8	26%	100%	5%	3.1
Heavy-duty CAFÉ					8.1	29%	100%	5%	2.2
VMT reduction					11.8	20%	100%	included	2.4
Freight energy savings					9.8	20%	100%	included	2.0
Air travel					3.0	40%	100%	5%	1.1
CVR and reduced T&D losses					35.0	3.8%	100%	0%	1.3
Power generation heat rate improvement					35.0	5.6%	100%	0%	2.0
Subtotal									39.8
Remaining consumption									60.1
Adjustments for overlap									
CAFÉ and VMT									0.6
CAFÉ, air freight and freight									0.6
CVR/T&D losses and electric use									0.4
Heat rate improvement and electric use									0.7
Subtotal									2.4
Total without indirect rebound									62.5
Addition for indirect rebound									3.5
Remaining consumption after adjustments									66.0

Notes:

- Assumptions for individual measures explained in table A3.
- As discussed in the text, based on a review of many rebound studies by Nadel (2016b), we generally factored in a direct rebound of 10% for most residential measures and 5% for the commercial sector and vehicle and aviation measures. In a few cases (as noted in the text), rebound is either already factored into the savings estimates or there is no evidence of direct rebound. In addition, our savings calculations factor in 10% indirect rebound, which is applied to all measures except the two power sector ones. We do not include indirect rebound on power sector measures, because we assume these measures will have negligible impact on consumer behavior since consumers will not be aware of the improvements and will see little impact on their energy prices (the costs of these measures will generally be only a little lower than the savings) .
- In many cases, the baseline energy use numbers include adjustments to eliminate savings from prior measures. In the case of vehicle, freight, VMT, T&D, and power plant improvements, we did not make these adjustments and hence we subtract the overlap at

the bottom of the table. We then allocated these adjustments to individual measures before preparing figures 3–6.

- For the high renewable energy scenario discussed in the text, all assumptions are the same, except that we adjusted the share of renewable electricity up to 50%, reducing the share of gas to 25% and of coal and nuclear to 12.5% each. The same heat rates are used for each of the energy sources, but due to changes in their relative share, the weighted average heat rate in 2040 in this scenario declines from 6,965 Btus/kWh in our efficiency case to 5,920 Btus/kWh in the high renewables case. This improved heat rate in turn affects the efficiency of electric vehicles when electric system losses are incorporated.

Table A2. Carbon dioxide savings by measure

		Elec	NG	Oil	Gasoline	Coal	Propane	E85	Jet fuel	Avia. gas	CO2
MMT CO2/quad		36.89314	53.07	73.16	71.30	95.35	63.07	14.8	70.90	69.20	(MMT)
Reference case		% of energy savings by fuel (2040)									5,044
Measure	Q saved										Savings
Appliance and equipment efficiency	4.7	68.7%	23.2%	4.3%	0.1%	0.4%	1.3%				196
ZNE new commercial buildings	2.7	76.9%	18.9%	2.0%	0.3%	0.3%	1.0%				110
ZNE new homes	2.1	71.5%	23.6%	1.4%	0.0%	0.0%	1.7%				88
Smart buildings	2.2	76.9%	18.9%	2.0%	0.3%	0.3%	1.0%				91
Smart homes	0.6	71.5%	23.6%	1.4%	0.0%	0.0%	1.7%				25
Residential retrofits	1.7	71.5%	23.6%	1.4%	0.0%	0.0%	1.7%				68
Commercial building retrofits	2.5	76.9%	18.9%	2.0%	0.3%	0.3%	1.0%				102
Behavior change in homes & buildings	1.0	74.2%	21.2%	1.7%	0.2%	0.1%	1.4%				42
Industrial efficiency improvements	7.8	29.1%	31.9%	29.2%	0.0%	3.3%	0.0%				408
CHP	0.5	100.0%									17
Light-duty CAFÉ	3.1	More detailed calculations done comparing reference and EE cases									282
Heavy-duty CAFÉ	2.2	0.0%	5.5%	85.1%	9.2%	0.0%	0.2%				160
VMT reduction	2.4	1.0%	0.2%	6.0%	89.9%	0.0%	0.1%	2.2%			164
Freight energy savings	2.0	0.0%	5.5%	85.1%	9.2%	0.0%	0.2%				141
Air travel	1.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	99.3%	0.7%	81
CVR and reduced T&D losses	1.3	100.0%									49
Power generation heat rate improvement	2.0	100.0%									73
Subtotal	39.8										2,096
Remaining emissions	60.1										2,948
Adjustments for overlap											
CAFÉ and VMT	0.6	1.0%	0.2%	6.0%	89.9%	0.0%	0.1%	2.2%			42
CAFÉ, air freight and freight	0.6	0.0%	5.5%	85.1%	9.2%	0.0%	0.2%				40
CVR/T&D losses and electric use	0.4	100.0%									17
Heat rate improvement and electric use	0.7	100.0%									27
Subtotal	2.4										126
Total without indirect rebound	62.5										3075
Addition for indirect rebound	3.5										197
Remaining emissions after adjustments	66.0										3,272

Notes:

- Quads saved from table A1.
- Emissions factors of MMT of CO_2 per quad from the 2016 AEO (EIA 2016a).
- Percentage of energy savings by fuel based on 2040 projections by end use in the 2016 AEO.
- In the case of light duty CAFÉ, we calculated emissions separately for the reference and energy efficiency cases. These calculations include emissions associated with electric vehicles in each case.
- For the high renewable energy scenario discussed in the text, we use the same emissions factors as in the primary analysis, but due to the greater use of carbon-free electricity generation, emissions per kWh are lower.

Table A3. Key assumptions and sources by measure

Measure	Baseline energy use	Savings	% applies to
Appliance and equipment efficiency	In deLaski et al. 2016	Specific savings number from deLaski et al. 2016. Added 17% for additional standards that take effect in the 2030s, which is a crude estimate of similar additional savings in half the products and for an average of five years of savings by 2040 for the new products instead of the typical 15 years for full turnover of the stock (5*0.5/15=17%). Multiplied savings by 134% to add savings from ENERGY STAR products program based on the average ratio of ENERGY STAR product savings to appliance and equipment standard savings over the 2005–2015 period.	In deLaski et al. 2016
Zero net energy (ZNE) new buildings and homes	For homes, assumed new construction equal to 1.5% of the stock each year (derived from AEO's survival rate); energy use per new home in AEO. For buildings, new floor area in AEO. Assumed new buildings use 10% less energy per sq. ft. than the building stock.	For 2017–2030, 37% average for homes, 40% for commercial buildings (from York et al. 2015a). For 2031–2040, 80% average. For both homes and buildings, assume code coverage expanded to include all energy use.	For 2017–2030, 38% average participation (from York et al. 2015a). For 2031–2040, 80% due to widespread ZNE codes, but 20% of homes and buildings either energy intensive and not ZNE or in states without such codes.
Intelligent buildings and homes	Used AEO, subtracting savings from the above two measures.	28% in commercial buildings (from Rogers et al. 2013). 12% HVAC savings in homes from learning thermostats (from York et al. 2015a). We add 6% savings for other end uses accounting for 30% of residential energy use (educated guess). We do this by multiplying the residential "% applies to" number by 1.5.	Rogers et al. 2013 estimate 50% achieved in commercial buildings by 2035; we increase to 60% for 2040. For learning thermostats or equivalent, we estimate 80% by 2040 and apply this to the 37% of 2040 home energy use that is for HVAC.
Home and building retrofits	Used AEO, 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 50%).	50% for homes (about 2%/year); 75% for commercial buildings (about 3%/year).

Measure	Baseline energy use	Savings	% applies to
Behavior change in buildings	Used AEO, subtracting savings from the above measures.	4% on average. We take 6% median from Navigant 2016, but take two-thirds of this as explained in the text.	100%, as savings to the left is an average for all customers, considering both high savers and zero savers.
Industrial efficiency improvements	Used AEO, subtracting savings from industrial share of equipment standards and subtracting 0.4% for estimated reduction in refinery energy use due to higher penetration of electric vehicles.	21% (compound rate of 1%/year as discussed in text).	100%, as savings to the left is an average for all customers, considering both high savers and zero savers.
Combined heat and power (CHP) systems	Incorporated into DOE (2016b) and Kelly (2016) estimates.	47,315 MW cost-effective potential and 4,437 full load annual operating hours, both from Kelly 2016. Estimate 40% average savings from CHP (other 60% is fuel used by CHP system), where 40% is based on 4,200 average heat rate for CHP systems (N. Elliott, ACEEE, pers. comm., October 21, 2016) and the average 2040 electric sector heat rate calculated in this report.	Estimate 80% of economic potential will be achieved by 2040.
Light and heavy duty vehicle fuel economy	From AEO	Based on 60 mpg nominal (48 on the road) for fuel vehicles, 52 on the road for electric. The latter estimate is based on 114 mpg for EVs on the road minus losses from generation and T&D.	100%, as savings to the left is an average for all vehicles, considering both high savers and zero savers.
Reductions in passenger vehicle miles traveled	From AEO	20%; rationale discussed in text	100%, as savings to the left is an average for all drivers, considering both high savers and zero savers.
Reductions in freight transport energy use	From AEO	20%; rationale discussed in text	100%, as savings to the left is an average for all shipments, considering both high savers and zero savers.
Aviation efficiency improvements	From AEO	40%, interpolating for 2040 in Greene and Plotkin 2011	100%, as savings to the left is an average for all users, considering both high savers and zero savers.

Measure	Baseline energy use	Savings	% applies to
Reductions in CVR and T&D loss	Energy use for electricity from AEO, subtracting electric savings from above measures, adjusting heat rate for renewable energy to 3,412, and adding electricity needed for additional electric vehicles in our scenario beyond those in AEO.	2.3% reduction for CVR (from York et al. 2015a), plus 1.5% reduction from reduced T&D losses Explained in text	100%, as savings to the left is an average for all circuits, considering both high savers and zero savers.
Reductions in power plant heat rates	Same as above, except also subtract CVR/T&D savings from the base.	5.6% based on improving coal and gas plants to midway between current heat rates and best current plants, plus modest improvements to nuclear heat rates (as explained in text).	100%, as savings to the left is an average for all generating plants, considering both high savers and zero savers.