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GCAM-USA Analysis of U.S. Electric Power Sector Transitions

May 2017

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Richland, Washington 99352

Abstract

The United States has developed a Mid-Century Strategy to reduce economy-wide greenhouse gas (GHG) emissions to 80% or more below 2005 levels by 2050.[1] Achieving these reductions will entail a major transformation of the energy system, including the electric power sector.[2,3] This study uses a detailed state-level model of the U.S. energy system embedded within a global integrated assessment model (GCAM-USA) to explore pathways for the evolution of the U.S. electric power sector that achieve 80% economy-wide reductions in GHG emissions by 2050. The pathways presented in this report build on the existing literature for similar emissions pathways as well as feedback received during a workshop of experts organized by the U.S. Department of Energy's (DOE) Office of Energy Policy and Systems Analysis. Consistent with previous analyses, the scenarios in this study include a substantial decarbonization of the electric power sector, increased electrification of end-use sectors, and increase in the deployment of low- and zero-carbon technologies such as renewables, nuclear and carbon capture utilization and storage. The results show that the degree to which the electric power sector will need to decarbonize depends on the nature of technological advances in the energy sector, and the degree to which end-use sectors electrify.

[1] The White House, United States Mid-Century Strategy for Deep Decarbonization (Washington, D.C., November 2016): 22, https://obamawhitehouse.archives.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf (Accessed 1 February 2017).

[2] Allen A. Fawcett, Leon E. Clarke, and John Weyant, The EMF 24 Study on U.S. Technology and Climate Policy Strategies, *The Energy Journal* 35, Special Issue 1 (2014).

[3] Deep Decarbonizaton Pathways Project (DDPP), *Pathways to deep decarbonization 2015 report*, SDSN-IDDRI (2015), http://deepdecarbonization.org/wp-content/uploads/2016/03/DDPP_2015_REPORT.pdf (Accessed 16 December 2016).

Acknowledgments

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Contents

1.0 Introduction

The United States has set targets to reduce economy-wide greenhouse gas (GHG) emissions in the range of 17% below 2005 levels by 2020[4], and 26–28% below 2005 levels by 2025. Both of these targets put the United States on a path towards 80% or greater reductions below 2005 levels by 2050 (referred to as 80% reductions in the rest of the report).[5] Previous studies, including the Energy Modeling Forum-22 (EMF-22), the Energy Modeling Forum-24 (EMF-24) and Deep Decarbonization Pathways Project (DDPP), have explored the implications of comparable emissions reductions for the United States.[6,7,8] These studies find that achieving 80% reductions will require a major transformation of the energy system in the near- and long-term. In particular, the studies show that least-cost pathways toward 80% reductions will entail substantial decarbonization of the electric power sector over the next 35 years, with reductions in that sector typically exceeding 80% (Figure 1).[9,10] In addition, the studies suggest that transitions in the electric power sector will depend, among other factors, on the character of technological advances, electrification of end-use sectors, and the efficiency of end-use electricity-fueled equipment and vehicles in the future.[11,12]

This study uses a detailed state-level model of the U.S. energy system embedded within a global integrated assessment model (GCAM-USA) to present illustrative scenarios of how the U.S. electric power sector might evolve. The scenarios presented in this study are intended to inform the following questions: ***What technology shifts would be necessary in the U.S. energy sector in general and in the electric power sector in particular to achieve 80% economy-wide emissions reductions? Within this context, how would advances in technology, the level of electrification, and electricity demand impact the nature of transitions in the U.S. electric power sector?***

This study builds on the EMF-22, EMF-24 and DDPP studies in two important ways. First, the scenarios presented in this report incorporate comments and feedback from a panel of experts across academia, national laboratories, industry, and non-governmental organizations in the United States during the Low Carbon Futures of the U.S. Energy System Workshop (Low Carbon Futures Workshop) organized by the U.S. Department of Energy's Office of Energy Policy and Systems Analysis (EPSA) on

[4] Todd Stern to Yvo DeBoer, January 28, 2010, United States Department of State, Office of the Special Envoy on Climate Change, Memorandum, http://unfccc.int/files/meetings/cop_15/copenhagen_accord/application/pdf/unitedstatescphaccord_app.1.pdf (Accessed 1 February 2017).

[5] The White House, Mid-Century Strategy.

[6] Fawcett et al, *EMF 24*.

[7] DDPP, *Pathways to Deep Decarbonization*.

[8] Allen A. Fawcett, Katherine V. Calvin, C. Francisco, John M. Reilly, and John P. Weyant, "Overview of EMF 22 US transition scenarios," *Energy Economics* 31 (2009): S198-S211.

[9] Fawcett et al, *EMF 24.*

[10] DDPP, *Pathways to Deep Decarbonization*.

[11] IPCC, Fifth Assessment Report (IPCC 2014).

[12] Fawcett et al, *EMF 24*.

January 14, 2016 (A full summary of this workshop is included in Appendix B). Second, the assumptions in our model have been updated based on more recently available knowledge of the U.S. economy and technology characteristics such as cost and performance and their evolution in the future.

The structure of this report is as follows. We first provide an overview of the EMF-22, EMF-24, and the DDPP studies and a summary of the Low Carbon Futures Workshop that motivated the development of the scenarios in this study. We then discuss the model used to develop these scenarios (GCAM-USA). The subsequent sections of the report describe the development of a reference scenario and sensitivity scenarios that vary across technology and electricity demand assumptions, followed by a discussion of our results.

2.0 Background

2.1 Overview of the literature on U.S. 80% reduction scenarios

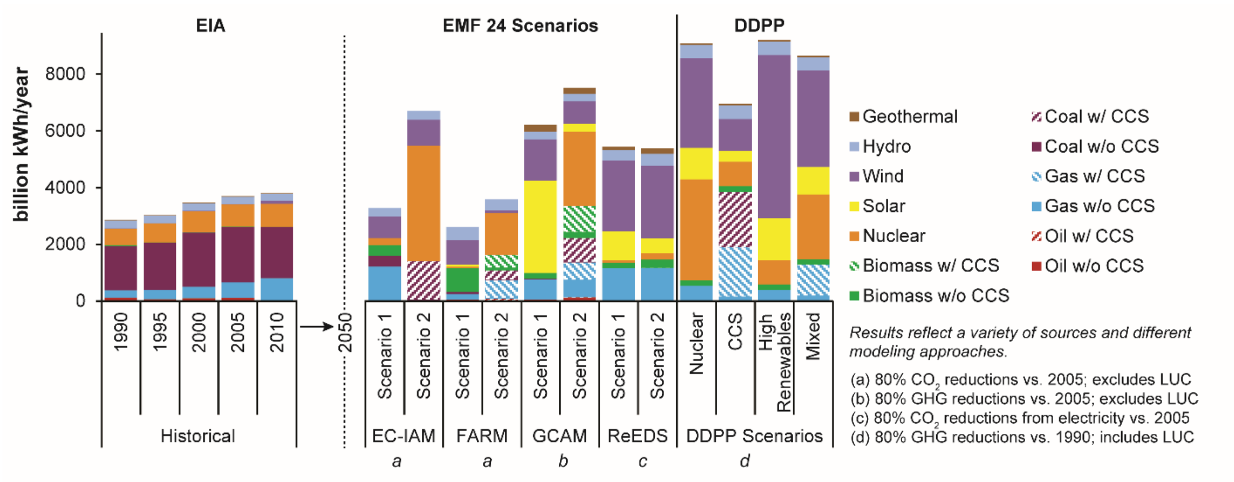

Figure 1: Electric Power Sector Transformations in 80% Economy-Wide GHG Emissions Reductions Scenarios (EMF-24 and DDPP).[13,14] Historical data is from the U.S. Energy Information Administration (EIA).[15,16,17,18,19]

The EMF-22, EMF-24 and DDPP studies explore emissions pathways that achieve 80-83% reductions in economy wide GHG emissions by 2050, relative to 2005 levels. [20,21,22] The EMF-22 and EMF-24 studies in particular are inter-model comparison exercises based on a diverse set of economy-wide energy-economic, integrated assessment, or electric sector models that vary across modeling approaches and assumptions. Despite the diversity across models used in the studies, the studies offer consensus on a number of broad insights. Two of these are most relevant for this study.

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[13] DDPP, *Pathways to Deep Decarbonization*.

[14] Fawcett et al, *EMF-22*.

[15] EIA, *Annual Energy Outlook*, DOE/EIA-0383(92) (Washington, D.C.: U.S. Energy Information Administration, 1992), 64-65.

[16] EIA, *Annual Energy Outlook*, DOE/EIA-0383(97) (Washington, D.C.: U.S. Energy Information Administration, 1996), 108.

[17] EIA, *Annual Energy Outlook*, DOE/EIA-0383(2002) (Washington, D.C.: U.S. Energy Information Administration, 2001), 126-128.

[18] EIA, *Annual Energy Outlook*, DOE/EIA-0383(2007) (Washington, D.C.: U.S. Energy Information Administration, 2007), 151.

[19] EIA, *Annual Energy Outlook*, DOE/EIA-0383(2013) (Washington, D.C.: U.S. Energy Information Administration, 2013), 123-125.

[20] Fawcett et al, *EMF-24*.

[21] DDPP, *Pathways to Deep Decarbonization*.

[22] Fawcett et al, *EMF-22*.

First, achieving 80% reductions will entail a rapid and significant restructuring of the energy system. The U.S. energy system is currently dominated by fossil fuels, which account for 66% of U.S. electricity generation. End-use sectors are also heavily reliant on fossil fuels for direct use, which account for over 99% of transportation, about 61% of industrial, and about 25% of residential and commercial buildings energy consumption.[23] The scenarios in these studies involve major shifts within the electric power sector from fossil fuels toward low- and zero-carbon technologies such as renewables, nuclear and carbon capture utilization and storage (CCUS).

Second, the range of scenarios in the EMF-22, EMF-24 and DDPP studies confirms that there are many different ways to achieve 80% economy-wide emissions reductions. The studies suggest that these emissions reductions can be achieved with only modest improvements in technology; more substantial improvements in technology can ease the challenge. Furthermore, achieving 80% reductions is not contingent upon the progress of a single low- or zero-carbon technology, and a portfolio approach that includes multiple technologies leads to lower costs of achieving 80% reductions than relying on a particular technology.

2.2 Summary of the Low Carbon Futures Workshop

The Low Carbon Futures Workshop focused on understanding key issues associated with substantial GHG emission reductions in the electric power sector (see Appendix B). It focused in particular on economy-wide GHG emissions reductions of 80% by 2050, relative to 2005 levels. Two key topics of discussion at the workshop that motivated the development of the scenarios in this report are as follows.

1. *The role of technology innovation*: Participants suggested that technology innovation over the coming decades could have a profound influence on the likelihood of pathways towards 80% reductions. We therefore explore the role of advances in end-use and electric power sector technologies in our scenarios.

2. *The need to integrate the demand-side and the supply-side*: On the one hand, reductions in electricity demand can reduce the magnitude of low- and zero-carbon electricity technology deployments that are needed to reduce economy-wide GHG emissions by at least 80% by 2050, relative to 2005 levels. On the other hand, electrification of the transportation, buildings and industrial sectors might be a key element of pathways toward 80% reductions, resulting in increased demand for low- and zero-carbon investments in the electric power sector.[24] While some participants suggested that major reductions in electricity use are possible, others suggested that options to reduce electricity use are less accessible.

Consistent with these comments, this study considers two scenarios characterized by lower technology costs and improved performance to explore the role of technology innovation in achieving 80% reductions in economy-wide GHG emissions – the *Advanced Technology +80%* and the *Stretch Technology +80%* scenarios. Furthermore, we explore two scenarios to account for the balance of supply and demand of electricity – *High Electrification +80%* and *Reduced Demand +80%* – with high and low levels of electricity demand, respectively.

[23] U.S. Energy Information Administration, *Annual Energy Outlook 2016 with Projections to 2040*, Washington, D.C., 2016.

[24] Fawcett et al, *EMF-24*.

3.0 Overview of the scenarios explored in this report

Building on previous literature and informed by the Low Carbon Futures Workshop, this study explores six scenarios constructed using GCAM-USA (Section 4) as described below. A brief description of each scenario follows. The detailed inputs are shown in Appendix A: Figures and Appendix A: Tables. The first of these is a reference scenario.

1. ***Reference***: This scenario is based on a reference set of assumptions about socioeconomic development, energy demand, and technology costs and performance based on the *Annual Energy Outlook 2016 Reference case?*[25] This scenario and all other scenarios include representations of existing U.S. electric power sector policies, including the Clean Power Plan, New Source and Performance Standards, the Investment Tax Credit, and the Production Tax credit.[26, 27]

The remaining five scenarios assume economy-wide U.S. GHG emissions reductions relative to 2005 levels of 17% in 2020 (corresponding to the United States' target announced during the Conference of Parties – 15 at Copenhagen), 27% in 2025 (corresponding to the U.S. Nationally Determined Contribution, NDC, for the Conference of the Parties – 21 at Paris), and 80% in 2050 (corresponding to the Mid-century Strategy). Further, the emissions path between 2025 and 2050 is assumed to be linear. These five scenarios assume the economy-wide emission constraints plus additional assumptions as follows:

2. ***Reference +80%***: This scenario includes the same assumptions as in the Reference scenario.
3. ***Advanced Technology +80%***: This scenario represents one potential low- and zero-carbon technology future based on current research, development, demonstration and deployment (RDD&D) funding levels and assumes all current U.S. Department of Energy (DOE) program goals (as modeled) are achieved, including reduced cost, increased performance, increased efficiency and accelerated deployment.
4. ***High Electrification +80%***: Starting with the *Advanced Technology +80%* assumptions, this scenario assumes high electrification of end-use sectors, for example through increased penetration of electric vehicles in the transportation sector and increased penetration of electric technologies in the buildings and industrial sectors[28].
5. ***Reduced Demand +80%***: Starting with the *Advanced Technology +80%* assumptions, this scenario explores the implications of broader measures for reducing overall energy demand (including demand

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[25] U.S. Energy Information Administration, *Annual Energy Outlook 2016 with Projections to 2040.*

[26] Environmental Protection Agency, "Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units", 80 Federal Register 205 (23 October 2015) (40 CFR Part 60): 64663, https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22842.pdf.

[27] Consolidated Appropriations Act of 2016, https://www.gpo.gov/fdsys/pkg/BILLS-114hr2029enr/pdf/BILLS-114hr2029enr.pdf (Accessed 8 May 2017).

[28] The representation of the industrial sector in GCAM-USA is at a very aggregate level and high electrification of the sector is achieved rather simply by adjusting preference parameters in GCAM-USA. A more detailed representation of the industrial sector is reserved for future work.

for electricity), such as smart growth strategies, which include lower building floorspace growth and reduced demand for light duty vehicles.[29]

6. ***Stretch Technology +80%***: This scenario explores the impact of additional funding for RDD&D (such as through Mission Innovation[30]) that enables a greater level of technological progress compared to the *Advanced Technology +80%* scenario, including reduced costs, increased performance and accelerated deployment of clean energy technologies.

4.0 GCAM-USA

The scenarios in this report are based on a version of the Global Change Assessment Model (GCAM) with detailed representation of the U.S. energy system at the state level (GCAM-USA).[31] The global version of GCAM integrates a suite of dynamic-recursive models of the energy, economy, agriculture and land-use systems for 32 geopolitical regions, including the United States all under one consistent framework.[32,33,34,35] The analysis in this study is based on scenarios developed using a U.S.-focused version of GCAM (referred to as GCAM-USA in this report) that breaks the energy and economy components of the United States into 50 states and the District of Colombia in addition to modeling the simultaneous interactions of 31 geopolitical regions outside of the United States.[36,37] GCAM-USA tracks emissions of a range of GHGs and air pollutants endogenously based on the resulting energy, agriculture, and land use systems. GCAM-USA is a dynamic recursive model and operates in 5-year time-steps from 2010 (calibration year) to 2100. This report discuses model results through 2050 only.

The principal drivers of GCAM-USA are population growth, labor participation rates and labor productivity, technology cost and performance, and policies in the 50 states and the District of Columbia. The energy system formulation in GCAM-USA consists of detailed representations of extractions of depletable primary resources such as coal, natural gas, oil and uranium, in addition to renewable resources

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[29] The *Reduced Demand* scenario does not include any reductions in industrial energy demand.
[30] U.S. Department of Energy, "Mission Innovation at DOE", https://www.energy.gov/mission-innovation/mission-innovation-doe (Accessed 19 December 2016)

[31] Katherine V. Calvin et al, "Global Change Assessment Model", http://www.globalchange.umd.edu/gcam/ (Accessed 16 December 2016).

[32] James A. Edmonds, John F. Clarke, et al, "Stabilization of CO2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, andtransportation technologies", *Energy Economics* 26, Issue 4 (2004): 517-537.

[33] Son H. Kim, James Edmonds, et al, "The ObjECTS framework for integrated assessment: hybrid modeling of transporation", *The Energy Journal* 27 (2006): 63-91.

[34] T.M. Wigley, MAGICC/SCENGEN 5.3: User Manual Version 2 NCAR (2008).

[35] GCAM Documentation, http://jgcri.github.io/gcam-doc/toc.html.

[36] Yuyu Zhou, Leon E. Clarke, et al, "Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework", *Applied Energy* 113 (2014): 1077-1088.

[37] Ian Kraucunas, Leon E. Clarke, et al., Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA), *Climatic Change* 129 (2015), 573-588.

such as bioenergy, hydro, solar, wind and geothermal. In the default version of GCAM-USA, wind, geothermal, and residential rooftop photovoltaic (PV) technologies include resource costs that are calculated from exogenous supply curves that represent marginal costs that increase with deployment. Central station solar technologies are assumed to have constant marginal resource costs regardless of deployment levels, which is a model simplification. In the version of the model used in this study, wind, geothermal and residential rooftop PV resource curves are represented at the state level. However, resource curves for coal, oil and natural gas are modeled at the national level (state-level representation of these resources is currently a work in progress). Bioenergy production is modeled at the national level in the agriculture and land use module that determines the allocation of land to competing uses such as food crops, commercial biomass, forests, pasture, grassland, shrubs, desert, tundra, and urban land. The energy system determines the demand for bioenergy and the agriculture and land-use system determines the supply.

GCAM-USA also includes representations of the processes that transform these resources to final energy carriers which are ultimately used to deliver goods and services demanded by end users in the buildings, transportation, and industrial sectors. Key energy conversion sectors such as refining and electric power are modeled at the state-level. Likewise, GCAM-USA includes representations of energy demand in the industrial, buildings, and transportation sectors in each of the 50 states and the District of Columbia.

The electric power sector includes a representation of a range of power generation technologies including those fueled by fossil fuels (with and without carbon capture, utilization and storage, CCUS), renewables, bioenergy (with and without CCUS) and nuclear (see Table A1 in the appendix for a full list of technologies).[38] We assume uniform generation efficiencies, costs, and technology availability across states. Technological advancement is assumed to be exogenous and is represented by means of decreasing technology costs over time. As described in the following sections, this study considers scenarios with different levels of technological advancement.[39] The detailed assumptions are shown in Appendix A: Tables. Each technology has a physical lifetime, and once an investment is made, technologies operate until the end of their lifetimes or are shut down if the variable cost exceeds the market price. The deployment of technologies depends on relative costs and is achieved using a probabilistic formulation that is designed to represent decision making among competing options when only some characteristics of the options can be observed.[40]

While GCAM-USA is a useful tool to answer the questions of interest in this report, several limitations of the model bear attention. First, the version of the model used in this study does not include representations of time variation of load during one model time step which is 5-years, for example, in the

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[38] The deployment of hydroelectric power is influenced strongly by political and social influences, which often play a more important role than economic considerations. For this reason, future generation from hydroelectric power is set exogenously.

[39] The exogenous representation of technological advancement implies that the analysis is agnostic about the specific sources of technological advancement such as R&D, learning-by-doing or spillovers.

[40] John F. Clarke and James A. Edmonds, "Modelling Energy Technologies in a Competitive Market," *Energy Economics* 15, Issue 2(1993): 123-129.

form of load segments[41]. Another limitation is that the version of the model used in this study does not include detailed representations of all primary fuels such as coal, oil and gas at the state level. Finally, the version of the model used in this report represents industrial energy demand in the 50 states and District of Columbia in an aggregate manner, without explicitly representing the energy consumption in various industrial processes and manufacturing. Detailed representations of time variation of load, state-level representation of all primary fuels and disaggregation of the industrial sector are all currently work in progress. Future analyses will be required to understand the implications of these model improvements.

5.0 Development of the *Reference* scenario

The *Reference* scenario was developed with the overarching goal to harmonize key inputs of GCAM-USA with the Annual Energy Outlook (AEO). As explained below, key input variables in GCAM-USA that set the scale for the overall demand for energy in the end-use sectors—such as socioeconomics (population and GDP), residential and commercial building floorspace, vehicle miles traveled as well as technology costs and efficiency assumptions in the electric power, buildings, and transportation sectors—were harmonized to AEO. All assumptions are based largely on the assumptions to the AEO 2015 Reference scenario; however updates were made to make the socioeconomic and technology cost and performance assumptions consistent with the AEO 2016 Reference scenario.[42] The *Reference* scenario also includes current and planned policies in the electric power sector in line with AEO 2016.

5.1 Variables that set the scale of energy demand

5.1.1 Socioeconomic assumptions

We harmonized gross domestic product (GDP) and population assumptions through 2040 at the aggregate U.S. level to the AEO 2016 Reference cases (Figure 2). Beyond 2040, we extrapolated AEO projections to gradually match assumptions for the United States in the global version of GCAM. The per-capita GDP growth rate is applied equally to all states. Per-capita GDP is assumed to grow at a rate of 2.2-2.6% per year between 2017 and 2040, while population is assumed to grow at a rate of 0.5-0.8% per year between 2017 and 2040.

[41] Robert C. Pietzcker, Falko Ueckerdt, Samuel Carrara, Harmen Sytze de Boer, Jacques Després, Shinichiro Fujimori, Nils Johnson et al, "System integration of wind and solar power in Integrated Assessment Models: A cross-model evaluation of new approaches", *Energy Economics* (2016).

[42] U.S. Energy Information Administration, "Assumptions to AEO2016", http://www.eia.gov/outlooks/aeo/assumptions/ (Accessed 04 January 2017).

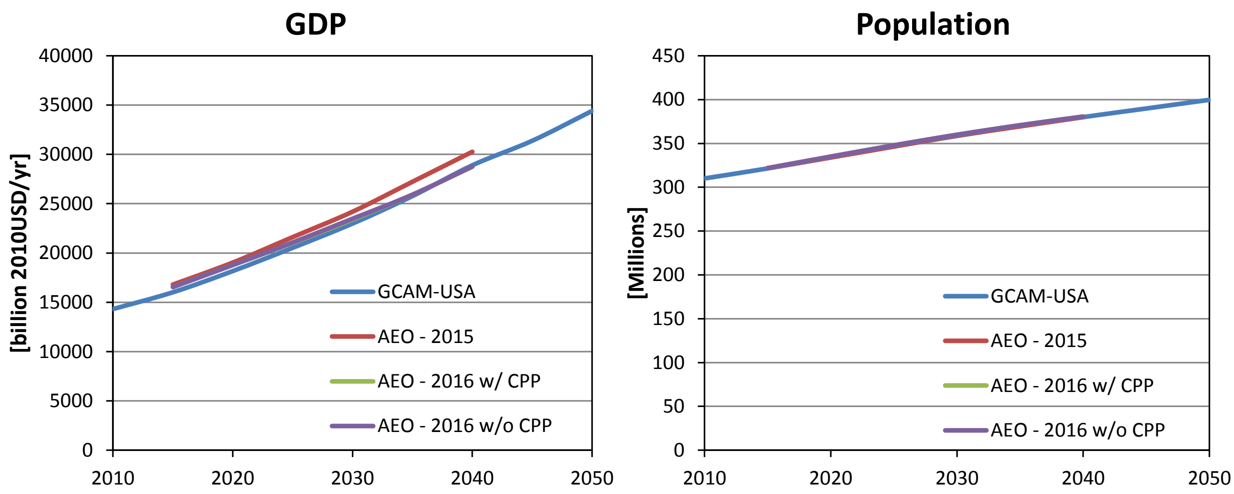

Figure 2: Gross domestic product (GDP) and Population assumptions in GCAM-USA

5.1.2 Floorspace and vehicle miles traveled assumptions

Building floorspace assumptions drive the demand for building energy services such as space heating and cooling. Floorspace assumptions in the *Reference* scenario are harmonized to AEO 2015 through 2040 (Figure 3). Beyond 2040, we extrapolate AEO 2015 projections to gradually match assumptions for the United States in the global version of GCAM. At the state level, for a given year, the difference between the national-level projection (from AEO 2015) and 2010 is allocated based on each state's share of U.S. population. In addition, we also harmonized assumptions about vehicle miles traveled that set the scale of demand for transportation services to AEO 2015 (Figure 4). Vehicle miles traveled for light-duty vehicles are projected to grow an average of 1% per year from 2017 to 2040, and vehicle miles traveled for medium and heavy duty vehicles are projected to grow an average of 1.1% per year.

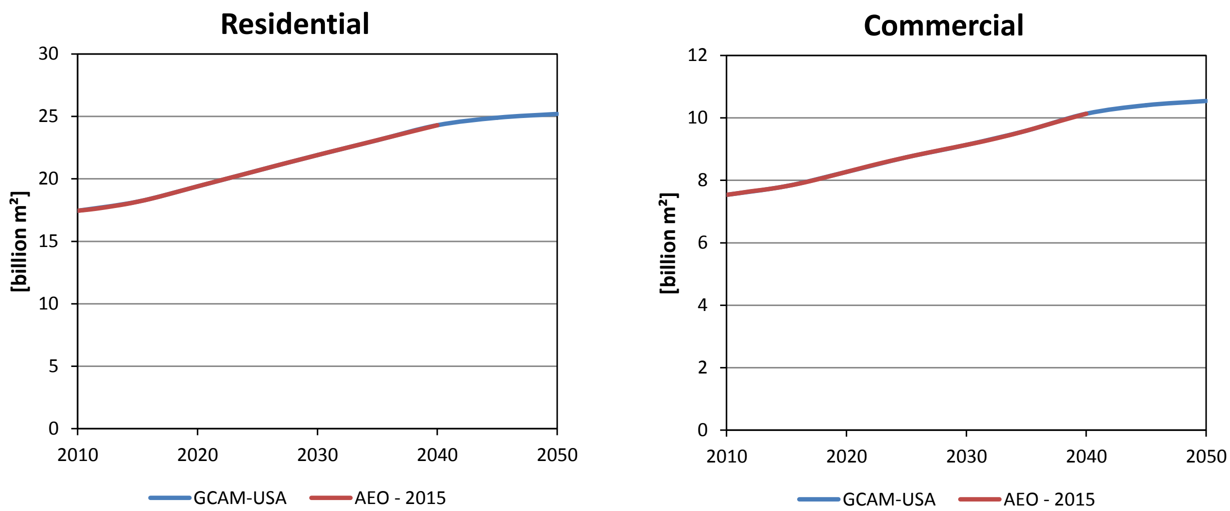

Figure 3: Floor-space assumptions for residential and commercial buildings in the GCAM-USA *Reference* scenario

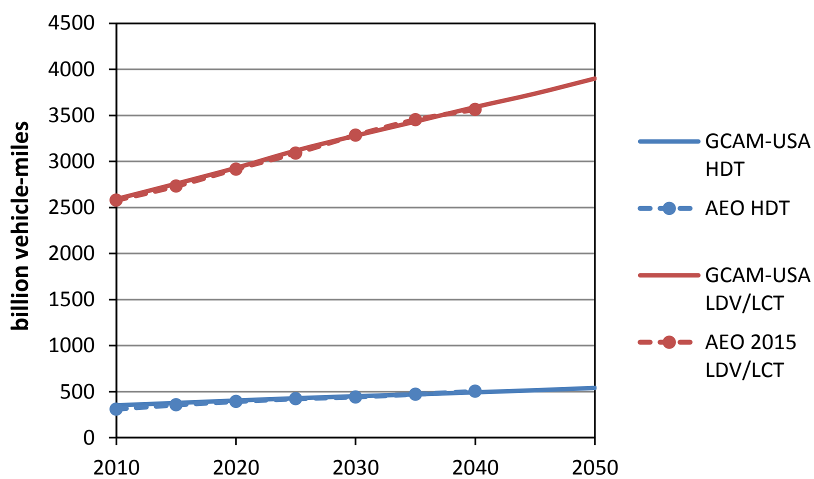

Figure 4: Vehicle miles traveled in the GCAM-USA *Reference* scenario, light duty vehicles and light commercial trucks and heavy-duty trucks.

5.2 Technology cost and performance assumptions

5.2.1 Electric power sector

GCAM-USA includes representations of a range of electric power technologies with a variety of fuel options including fossil fuels (with and without CCUS), renewables, nuclear, geothermal and bioenergy (with and without CCUS). These technologies are characterized by exogenous assumptions about capital costs, fixed and variable operating and maintenance costs, efficiency, capacity factors and lifetimes while fuel costs for the operation of electric power plants are calculated endogenously by the model. We harmonized power plant cost, efficiency and capacity factor assumptions in GCAM-USA in the *Reference* scenario to AEO 2016 (Tables A1-A3 in the appendix).

5.2.2 Buildings sector

GCAM-USA includes a detailed buildings sector that is divided into residential and commercial sectors. Both sectors model a set of services including space heating, lighting, water heating, and appliances. Each service contains a set of technologies that compete with one another for market share. Among these technologies are low and high-efficiency options that are powered by both secondary fuels (such as electricity and hydrogen) as well as direct use of primary fuels (such as coal and gas). Technologies in the buildings sector are characterized by exogenous assumptions about cost and efficiency while fuel costs are calculated endogenously. We harmonized buildings sector technology cost and efficiency assumptions in the *Reference* scenario to AEO 2016 (Tables A4-A7 in the appendix).

5.2.3 Transportation sector

The transportation sector is divided into freight and passenger vehicle classes, each of which contains on-road vehicle options such as cars, trucks, and motorcycles, as well as off-road options such as trains. In addition, these vehicle options include various drivetrain technologies such as liquid, hybrid, and electric. We harmonized capital cost, vehicle efficiency, and load factor assumptions for the various technologies in the transportation sector in the *Reference* scenario to AEO-2016 (Tables A8 and A9 in the appendix).

5.2.4 Industrial sector

The industrial sector in GCAM-USA is an aggregate representation of many diverse sectors. Specific industries such as cement and nitrogen fertilizer production are separated from the aggregate, while others are grouped into an 'industrial energy use' sector. The industrial energy use sector is organized by fuel consumption, with each subsector containing a set of technologies that consume a particular fuel. Technology assumptions in the *Reference* scenario are shown in Table A10 of the appendix.

5.3 Representation of electric power sector policies

The *Reference* scenario includes current electric sector policies including the New Source Performance Standards, Clean Power Plan, and the investment tax credits (ITC) and production tax credits (PTC).

5.3.1 New Source Performance Standards

The New Source Performance Standards (NSPS) were established in 2015 by the U.S. EPA and limit CO_2 emissions to 1400 lb CO_2/MWh for all newly constructed steam-generating electricity generation units, and to 1,000 or 1,030 lb CO_2/MWh for newly constructed base load natural gas fired units.[43] In our model, coal-fired power plants without CCUS do not meet the minimum requirements for these standards. Hence, no new coal-fired plants without CCUS come online in the scenarios explored in this study. However, natural gas combined-cycle plants without CCUS do come online in our scenarios, as they are assumed to meet the NSPS.

5.3.2 Clean Power Plan

The *Reference* scenario includes a representation of the Clean Power Plan (CPP) in the electric power sector.[44,45] The CPP is represented as a national mass-based cap on emissions from the power sector and assumes national trading of emissions permits.

5.3.3 Investment and Production Tax Credits

The *Reference* scenario includes the ITC and PTC, which are federal tax credits that are currently available for some types of low- and zero-carbon technologies in the electric power sector (Table A11).[46]

6.0 Development of the 80% reduction scenarios

In response to the feedback from the Low Carbon Futures Workshop, which was informed by scenarios in the literature, we consider five scenarios with 80% reductions: *Reference +80%* scenario, *Advanced Technology +80%*, *High Electrification +80%*, *Reduced Demand +80%* and *Stretch Technology +80%* scenarios. These scenarios include economy-wide GHG emissions constraints of 17% reduction in 2020, 27% reduction in 2025 and a linear reduction thereafter to an 80% reduction in 2050 from 2005. The model selects a mix of energy resources to meet the constraints. Note that all of the 80% scenarios also include the electric power sector policies described in Section 5.3. Furthermore, these scenarios assume consistent levels of climate mitigation policy in regions outside of the United States.

6.1 The Reference +80% scenario

The *Reference +80%* scenario includes the same assumptions as the *Reference* scenario, and incorporates emissions constraints of 17%, 27% and 80% reductions in economy-wide GHG emissions by

[43] Environmental Protection Agency, "Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units", 80 Federal Register 205 (23 October 2015) (40 CFR parts 60, 70, 71, and 98): 64513, 64546-64547, https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf (Accessed 16 December 2016).

[44] Environmental Protection Agency, "Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units".

[45] At the time of this analysis, the Clean Power Plan was a final regulation undergoing court review. At the time of publication, the Clean Power Plan was under executive review.

[46] Consolidated Appropriations Act of 2016, https://www.gpo.gov/fdsys/pkg/BILLS-114hr2029enr/pdf/BILLS-114hr2029enr.pdf (Accessed 8 May 2017).

2020, 2025 and 2050 respectively, relative to 2005 levels. In addition, the emission path between 2025 and 2050 is assumed to be linear. Furthermore, the *Reference +80%* scenario assumes consistent levels of climate mitigation policy in regions outside of the United States.[47]

6.2 The Advanced Technology +80% scenario

The *Advanced Technology +80%* scenario is characterized by faster technology cost reductions and performance improvements (Tables A12-A21 in the appendix). We modified inputs used for a separate analysis published by DOE[48], which focuses on the impacts of technology and policy on energy CO_2 emissions, for use in the GCAM-USA model framework. Importantly, this analysis includes an 80% economy-wide emission constraint, which was not included in the DOE analysis.[49] For the electric power sector, this scenario includes faster capital cost reductions for CCUS power plants, reduced costs for utility-scale solar PV systems, reduced capital costs for land-based wind power and geothermal, and reduced overnight capital and O&M costs for nuclear technologies compared to the *Reference* scenario (Tables A12-A13 in the appendix). In the buildings sector, this scenario represents increased stringency of residential and commercial appliance standards and building codes; lower cost and increased performance for equipment and appliances; increased availability of efficient technologies; improved new residential shell technology performance; and increased consumer adoption of high efficiency products compared to the *Reference* scenario (Tables A14-A18 and A21in the appendix). The transportation sector includes updated vehicle costs and improved fuel economy for all vehicle types in the transportation sector compared to the *Reference* scenario (Table A19 in the appendix). Finally, this scenario includes improved efficiency levels for all fuels in the industrial sector (Table A20 in the appendix). More information on the assumptions for this scenario can be found in the DOE report.[50]

6.3 The High Electrification +80% Scenario

The *High Electrification +80%* scenario is intended to reflect a pathway toward 80% reductions that represents a transition toward electrification in the energy end use sectors. Major changes to the *Reference +80%* scenario include the following.

In the electric power sector, input parameter assumptions are the same as the *Advanced Technology +80%* scenario.

In the transportation sector, the share of electric vehicles in the light, medium and heavy duty fleets increases out to 2050 to a level which represents what may be technically feasible based on a review of technology potential and current availability of battery electric vehicles (BEVs). In the light duty vehicle sector, BEVs are assumed to compete evenly on the basis of cost with internal combustion engine

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[47] The White House, Mid-Century Strategy.

[48] U.S. Department of Energy, "Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy (Accessed 18 January 2017).

[49] Note that the DOE analysis includes scenarios with carbon prices but that the DOE analysis does not include the 80% emissions constraint.

[50] U.S. Department of Energy, "Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy".

vehicles (ICEVs) by 2030. This assumption implies that currently existing non-economic barriers to deployment of BEVs do not exist in the future.[51] In the medium and heavy-duty vehicle sector, BEVs are assumed to compete evenly with ICEVs on the basis of costs by 2050. The above adjustments result in BEVs accounting for more than 80% of the light-duty vehicle service demand and 6% of the medium and heavy-duty service demand by 2050 (Figure A1 in the appendix). Vehicle cost and efficiency assumptions are identical to the *Advanced Technology + 80%* scenario (Table A19 in the appendix).

In the buildings and industrial sectors, technology preference parameters are adjusted.[52] In order to increase the share of electrification in the buildings and industrial sectors, PNNL modified preference parameters for the share of each fuel type in the buildings sector and parameters for the share of electricity in total industrial final energy use. These parameters are modified to follow a trajectory for technical potential of electrification as shown in Figures A2 and A3 in the appendix. The technical potential of electrification for buildings was determined by assuming a transition i) away from gas-powered water heaters and furnaces to heat pumps and electric resistance heaters, ii) from incandescent and florescent lighting to light-emitting-diodes (LEDs) and iii) from gas stoves to induction and other forms of efficient electrical cooking in residential and commercial applications.[53,54,55,56] The electrification potential for industry was determined by assuming increased electrification for process heating (for example, increased use of electrolytic reduction in nonferrous metals production, induction heating in metal fabrication, resistance heating and melting in glass, direct arc melting in iron and steel, and industrial heat pumps in food, paper, and chemicals) and conventional boiler use (increased use of electric boilers for all industries). The technical potential growth rates in the above industrial applications were developed by NREL based on the Electric Power Research Institute (EPRI) Electrotechnology Reference Guide (2010).[57]

All other input parameter assumptions in this scenario are the same as the *Advanced Technology +80%* scenario.

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[51] This scenario is constructed as a High Electrification only scenario rather than a "High Electrification and High Hydrogen" scenario. Hence, we assume that light duty fuel cell vehicles do not get market share in this scenario. In addition, because GCAM does not include hydrogen vehicles as a technology type in medium and heavy duty vehicles, hydrogen vehicles are never part of this scenario.

[52] Preference parameters alter the competition between technologies within a sector for market share. If two technologies have equal preference weights, competition will occur on the basis of cost. Preference weights may be altered in order to calibrate to observed technology shares, or to emulate the role of unquantified factors in competition, such as public acceptance and legal and institutional barriers.

[53] M. S. Horgan and D. J. Dwan, The Feasibility of LED Lighting for Commercial Use. Worcester Polytechnic Institute, 2014, https://web.wpi.edu/Pubs/E-project/Available/E-project-042914-123314/unrestricted/LED_MQP_Paper_Final_Dwan_Horgan.pdf (Accessed 20 February 2017).

[54] M. Wei, J.H. Nelson, J.B. Greenblatt, A. Mileva, et al. "Deep carbon reductions in California require electrification and integration across economic sectors." *Environmental Research Letters* 8 (2013): 014038.

[55] J. Greenblatt, M. Wei, and J. McMahon, "California's Energy Future: Buildings & Industrial Efficiency." Sacramento, CA: California Council on Science and Technology, 2012, http://ccst.us/publications/2012/2012bie.pdf (Accessed 20 February 2017).

[56] DDPP, *Pathways to Deep Decarbonization*.

[57] EPRI, "Electrotechnology Reference Guide 2010 (draft)", Palo Alto, CA: Electric Power Research Institute (EPRI), 2010.

6.4 The Reduced Demand +80% Scenario

The *Reduced Demand +80%* scenario is meant to demonstrate the implications of aggressive reductions in overall energy demand (including the demand for electricity) beyond what might potentially be achieved due to the improved end-use energy efficiency assumptions in the *Advanced Technology +80%*. This scenario is not intended to include a comprehensive set of end-use efficiency measures. Rather, this scenario is meant to be illustrative of a subset of options, as a way to demonstrate examples of the overall character of increased efficiency. This scenario explores the implications of broad demand-reducing measures such as smart growth, which include reduced building footprints through strategies that represent a shift in building trends toward compact homes and apartments, improved codes and standards for a range of building shell characteristics (such as wall and ceiling insulation), window and door specifications, roofs and foundations, and reduced demand for passenger transportation services.[58,59]

In the buildings sector, smart growth strategies are modeled by adjusting building floorspace which is a key driver of the demand for building energy services such as space heating and space cooling. Specifically, residential and commercial building floorspace in 2050 were assumed to be 25% lower than the *Reference* scenario, which is in the range of studies that estimate the potential for reduced demand for building floorspace.[60,61,62,63] This adjustment results in an increase in floorspace relative to current levels, however; the increase is less than for the *Reference +80%* scenario. The smaller floorspace assumptions in the *Reduced Demand +80%* scenario result in a reduction in building energy demand relative to the *Reference +80%* scenario of approximately 20%.

In the transportation sector, smart growth strategies are modeled by reducing the demand for total passenger transportation service (in terms of passenger kilometers traveled). In GCAM-USA, the demand for passenger transportation service in each state increases, among other variables, with income according to exogenously specified income elasticities. To implement this scenario, income elasticities are reduced such that total passenger transportation service demand in 2050 is roughly 20% lower than the *Reference +80%* scenario (Table A23 in the appendix). The reduction in passenger transportation service demand is in the range of studies that estimate the potential for such reductions through smart growth

[58] E. Sullivan and J Yeh, Smart Growth: State Strategies in Managing Sprawl, The Urban Lawyer 45(2): 349-405 (Spring 2013).

[59] Environmental Protection Agency, "Smart Growth And Climate Change", https://www.epa.gov/smartgrowth/smart-growth-and-climate-change (Accessed 6 February, 2017).

[60] R. Ewing, K. Bartholomew, S. Winkelman, J. Walters, and D. Chen, "Overview", In Growing Cooler: The Evidence on Urban Development and Climate Change, The Urban Institute, 2008, pp. 1-16.

[61] Cambridge Systematics Inc, Moving Cooler, Washington, D.C.: Urban Land Institute, 2009.

[62] M. A. Brown and F. Southworth, "Mitigating Climate Change through Green Buildings and Smart Growth." *Environment and Planning A* 40: 653-675 (2008).

[63] J. Walters and R. Ewing (2009). "Measuring the Benefits of Compact Development on Vehicle Miles and Climate Change." *Environmental Practice*, Volume 11, Issue 3. Pp. 196-208. http://www.tandfonline.com/doi/abs/10.1017/S1466046609990160

strategies.[64,65,66,67] This adjustment results in an increase in service demand relative to current levels, however; the increase is smaller than the *Reference +80%* scenario. The lower passenger transportation service demand in the *Reduced Demand +80%* scenario results in a reduction in transportation energy consumption relative to the *Reference +80%* scenario of approximately 20%.

All other input parameter assumptions in this scenario are the same as the *Advanced Technology +80%* scenario.

6.5 The Stretch Technology +80% scenario

In addition to the *Advanced Technology +80%* scenario, we consider a *Stretch Technology +80%* to explore the implications of accelerated technological innovation. This scenario is characterized by technology cost, performance, and deployment characteristics that reflect ambitious performance improvements and cost reductions enabled by additional RDD&D support. The inputs for this scenario are based on those used for a separate analysis published by DOE, 2017,[68] but the model is different between the two analyses. Note that this analysis modified only a subset of inputs considered in the analysis by DOE analysis as described in the *Advanced Technology +80%* scenario (the full list of inputs modified for this analysis is provided below). PNNL modified the DOE data to translate it into inputs appropriate for use in the GCAM model framework. Importantly, this analysis includes an 80% economy-wide emission constraint, which was not included in the DOE analysis.

In the electric power sector, this scenario includes lower cost parameters for a set of electricity generation technologies, including advanced nuclear, coal with CCUS, natural gas combined cycle with and without CCUS, land-based wind, and solar technologies compared to the *Advanced Technology +80%* scenario (Tables A12-A13). In the transportation and industrial sectors, this scenario represents lower capital and infrastructure costs for light duty hydrogen fuel-cell electric vehicles, improved fuel consumption metrics for liquid and hybrid liquid-fueled light duty vehicles (Table A19 in the appendix) and improved efficiency parameters for industrial technologies (Table A20 in the appendix) compared to the *Advanced Technology +80%* scenario. More information on the assumptions for this scenario can be found in DOE, 2017.[69]

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[64] Ewing et al, Growing Cooler, pp. 1-16.

[65] Cambridge Systematics Inc., Moving Cooler.

[66] EPRI, 2009, Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S., http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001016987 (accessed 13 February 2017).

[67] Ewing, R., K. Bartholomew, S. Winkelman, J. Walters & G. Anderson (2008). "Urban development and climate change." *Journal of Urbanism: International Research on Placemaking and Urban Sustainability,* Volume 1, Issue 3. Pp. 201-216. http://dx.doi.org/10.1080/17549170802529316

[68] U.S. Department of Energy, "Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy".

[69] U.S. Department of Energy, "Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy".

7.0 Results

7.1 The *Reference* scenario

Without an 80% economy-wide emission constraint, the electric power sector in the *Reference* scenario is characterized by an expansion of gas without CCUS, with some additional generation from renewables and coal with CCUS by 2050. This is because this scenario assumes, by construction, no new investments in coal power driven by the NSPS and the cheapest substitute for coal is gas. In addition, this scenario includes a representation of the Clean Power Plan, which is modeled as a national cap on power sector emissions. Hence, the resulting mix of technologies in the power sector represents a cost-effective mix of technologies to meet the cap while also satisfying the demand for electricity. By 2050, the share of wind and solar in total generation grows from roughly 2% in 2010 to about 15% in 2050. Furthermore, coal and gas with CCUS begin to come online in 2030 and by 2050, the share of these technologies is about 11%. Note that this reference run includes more CCUS than the 2017 Annual Energy Outlook.[70]

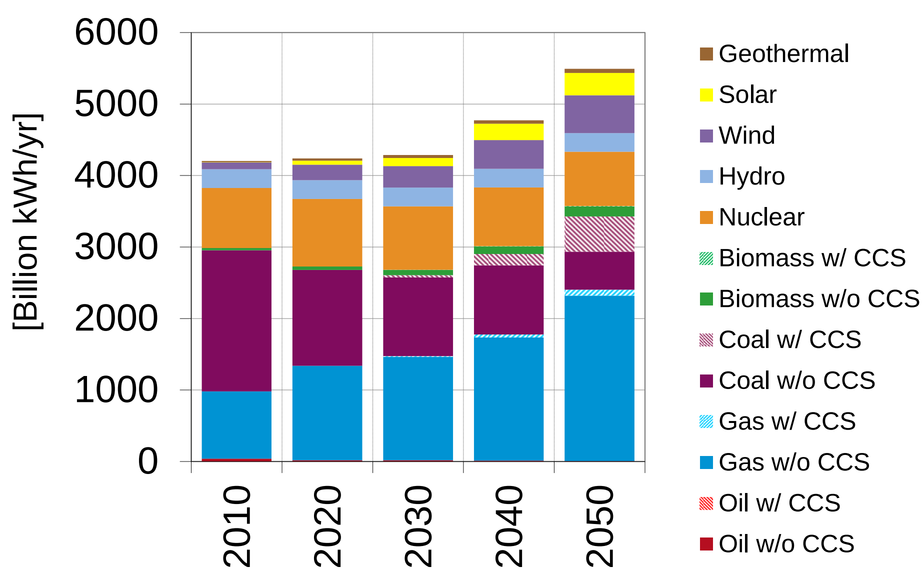

Figure 5: Electricity generation by technology under the Reference scenario without an economy-wide carbon constraint.

7.2 80% reduction scenarios

The 80% reduction scenarios explored in this study demonstrate multiple pathways toward 80% reductions by 2050. These pathways are characterized by a range of features. While some of the features are common across scenarios, some are unique. The most common characteristic across all of the scenarios is that the electric power sector is almost completely decarbonized (i.e., fossil fuel technologies without CCUS are almost completely phased out) by 2050 (Figure 6 and Figure A4 in the Appendix).

[70] Energy Information Administration, "Annual Energy Outlook 2017", January 2017, http://www.eia.gov/outlooks/aeo/ (accessed 18 January 2017).

Another common feature across the scenarios is the increase in the electrification of end-use sectors (Figures A5-7 in appendix) compared to the present. This is due to the availability of cheaper, lower carbon-emitting technologies in the electric power sector compared to other sectors, when an economy-wide emission constraint is applied. Consequently, electricity generation increases substantially in all of the scenarios in this analysis (Figure 6). For instance, under the *Reference +80%* scenario, electricity generation doubles from 4 trillion kilowatt-hours per year in 2010 to 8 trillion kilowatt-hours per year in 2050. The growth in electricity generation depends on the level of electricity demand. Under the *High Electrification +80%* scenario, with increased electrification of end-use sectors, electricity generation increases faster than the *Reference +80%* scenario, to about 9 trillion kilowatt-hours per year in 2050. In contrast, in the *Reduced Demand +80%* scenario, the growth in electricity generation is smaller, increasing to roughly 5 trillion kilowatt-hours per year in 2050. Note that the *Advanced Technology +80%* scenario is characterized by lower growth in electricity generation compared to the *Reference +80%* scenario, because the scenario represents significant improvements in end-use energy efficiency, in addition to lower-cost technologies, resulting in a net reduction in the demand for energy (including electricity) on the net. It is important to note that the increase in electrification in the 80% reduction scenarios explored in this study is driven by the economy-wide emission constraint. Another analysis that explores scenarios with the same technology assumptions as this study but with no economy-wide emission constraint does not find increases in electrification.[71]

Finally, all of the scenarios are characterized by a significant increase in the generation from low- and zero-carbon technologies compared to the present. However, the degree to which the deployment of such technologies is increased in these scenarios depends in part, on the nature of technological advance and in part on the level of electrification in the scenarios. For instance, the fraction of zero-carbon technologies deployed in the *Stretch Technology +80%* scenario, which includes substantially lower technology costs, is about 85% of total electricity generation compared with 64% in the *Reference +80%* scenario (Figure 6). The deployment of low- and zero-carbon technologies also depends on the level of electrification of end-use sectors and the efficiency of electricity consumption. For example, the deployment of low- and zero-carbon technologies in the *High Electrification +80%* scenario, with higher electrification of end-use sectors, is higher compared with the *Reference +80%* scenario while the deployment in the *Reduced Demand +80%* scenario is substantially lower Figure 6).

[71] U.S. Department of Energy, "Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy."

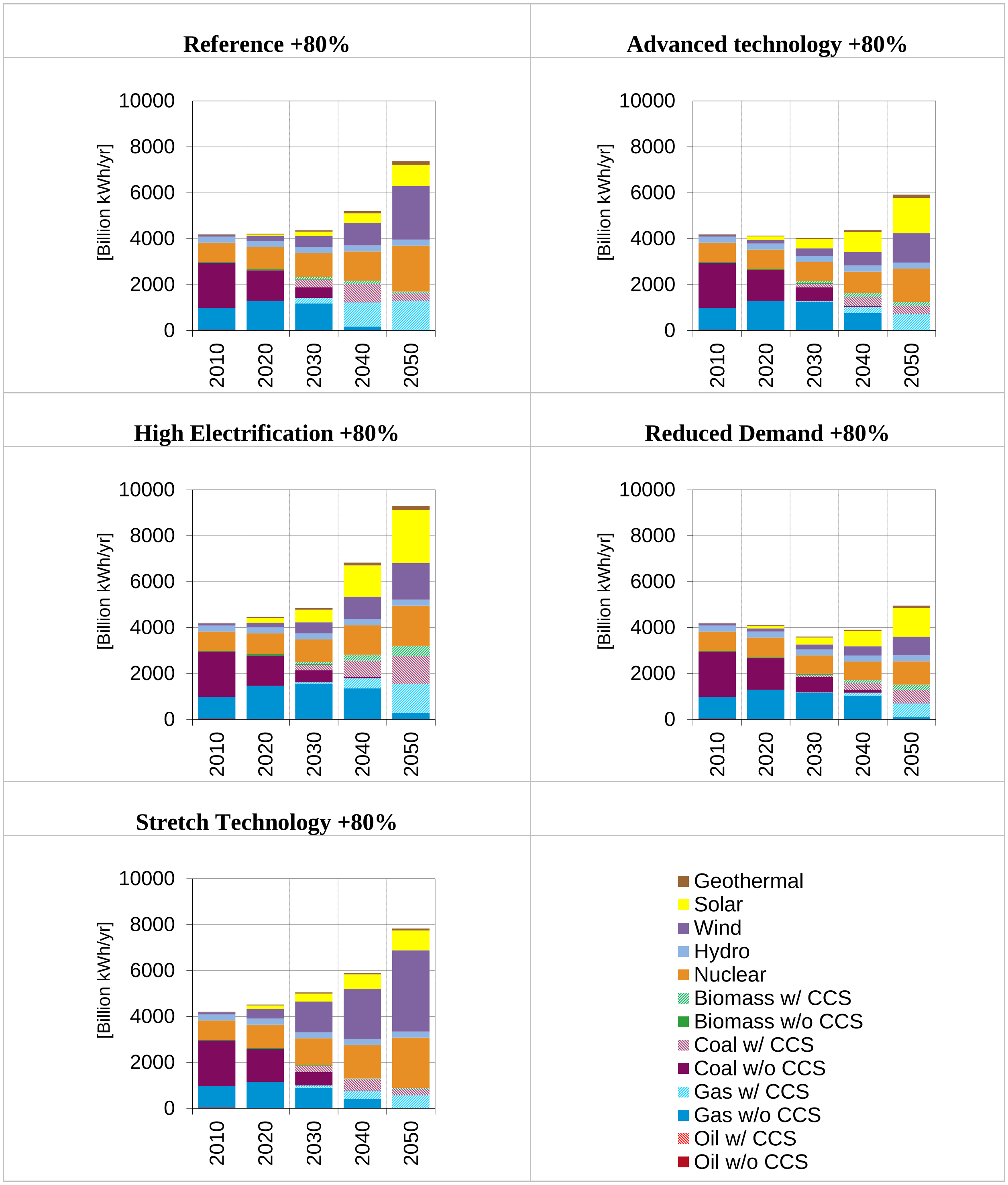

Figure 6: Electricity generation by technology under the 80% reduction scenarios explored in this report.

Some of the above observations resonate with those from similar analyses undertaken as a part of the EMF-24 and DDPP studies.[72,73] For example, similar to this study, most scenarios in the above studies find that more than 80% of all electricity generated in the United States would need to be provided by low- and zero-carbon sources to achieve economy-wide 80% reductions.

It is worth noting that the *Advanced Technology +80%* scenario modeled in this study results in different generation technology splits compared to a scenario utilizing similar technology cost and performance inputs, but implemented using a different model (EPSA-NEMS) and without the 80% reduction constraint. Some of the differences are due to the difference in emission constraints between the scenarios. Without the 80% reduction constraint in the EPSA-NEMS analysis, the deployment of CCUS is smaller compared to the case with a constraint and the level of electrification remains almost constant over the duration of the analysis (Figure 5). However, the amount of wind vs. solar generation differs between the two models, with more wind generation resulting from the EPSA-NEMS analysis.

Note that some scenarios in the EMF-24 and DDPP studies focus on futures where various technologies dominate the total share of electric generation. While such scenarios were explored in the Low Carbon Futures Workshop, they are not studied here. Instead, this study allows all generating technologies to compete based on projected future costs. This method results in a broad mix of generating technologies deployed to meet demand as shown in Figure 6.

8.0 Conclusions

This study uses a detailed state-level model of the U.S. energy system embedded within a global integrated assessment model (GCAM-USA) to explore illustrative power sector scenarios that achieve 80% reductions in economy-wide GHG emissions in 2050. The scenarios are informed by feedback from a workshop of experts organized by the U.S. Department of Energy's Office of Energy Policy and Systems Analysis, which was informed by previous literature on U.S. 80% reduction scenarios.[74]

The results from the scenarios demonstrate that achieving economy-wide 80% reductions by 2050 will require substantial decarbonization of the electric power sector. In all the scenarios explored in this report, fossil fuels without CCUS are almost completely phased out by 2050. While the fuel mix of the electric power sector will ultimately depend on a range of factors including policy and infrastructure, our scenarios illustrate that the deployment of low- and zero-carbon technologies in the power sector will need to be a key element of strategies to achieve 80% reductions. Finally, our results also demonstrate that the degree to which the electric power sector will need to be decarbonized and low- and zero-carbon technologies deployed will ultimately depend on the nature of technology advances in the energy sector, the extent to which end-use sectors electrify, and the level of energy demand.

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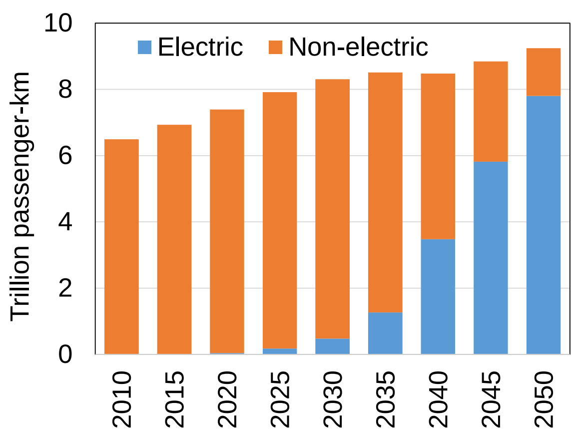
[72] Fawcett et al, *EMF-24*.

[73] DDPP, *Pathways to Deep Decarbonization*.

[74] Fawcett et al, *EMF-24*.

Appendix A: Figures

Light-duty vehicle passenger kilometers traveled



Freight ton-kilometers traveled

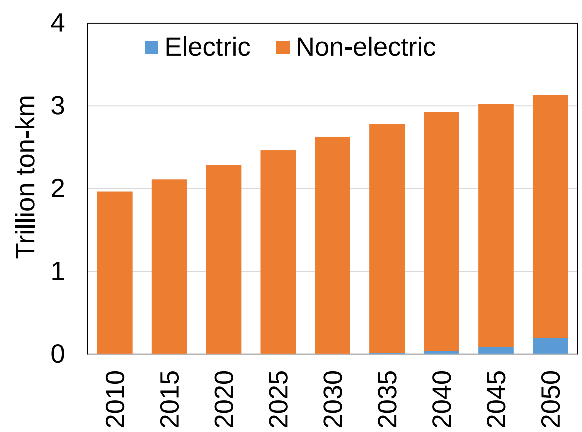


Figure A1: Transportation service by fuel type, *High Electrification + 80%* scenario

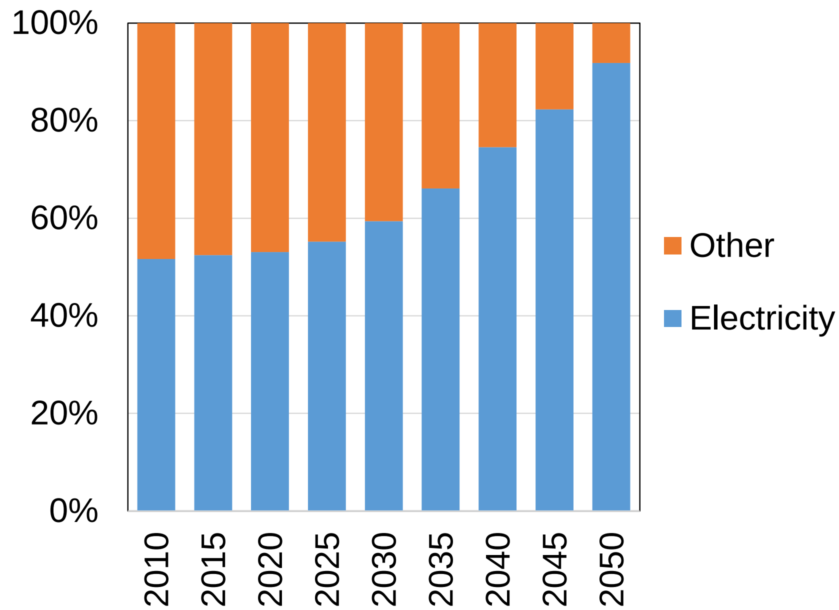


Figure A2: Share of Electricity Consumption, Buildings Sector, *High Electrification +80% Scenario*

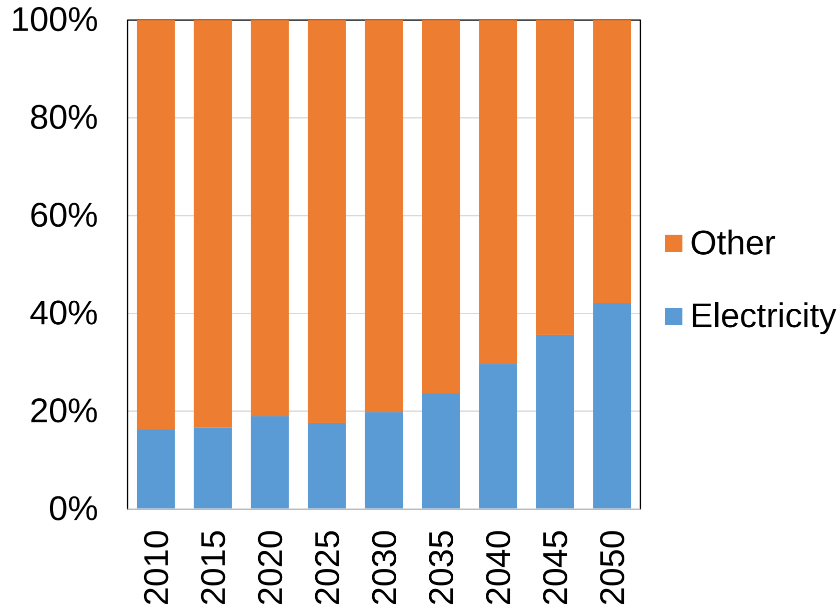


Figure A3: Share of Electricity Consumption, Industry Sector, *High Electrification +80% Scenario*

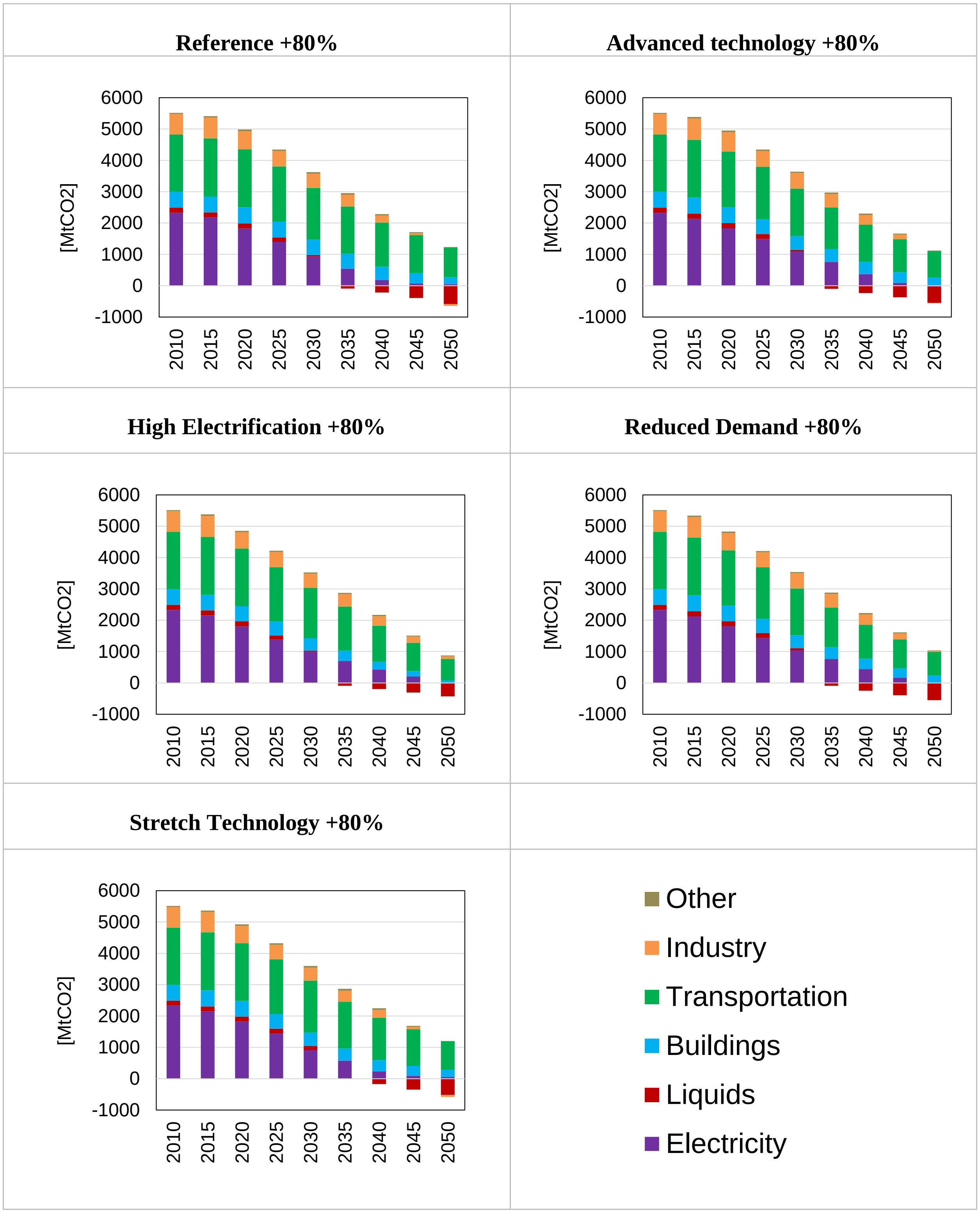


Figure A4: Sectoral breakdown of CO_2 emissions from the energy system

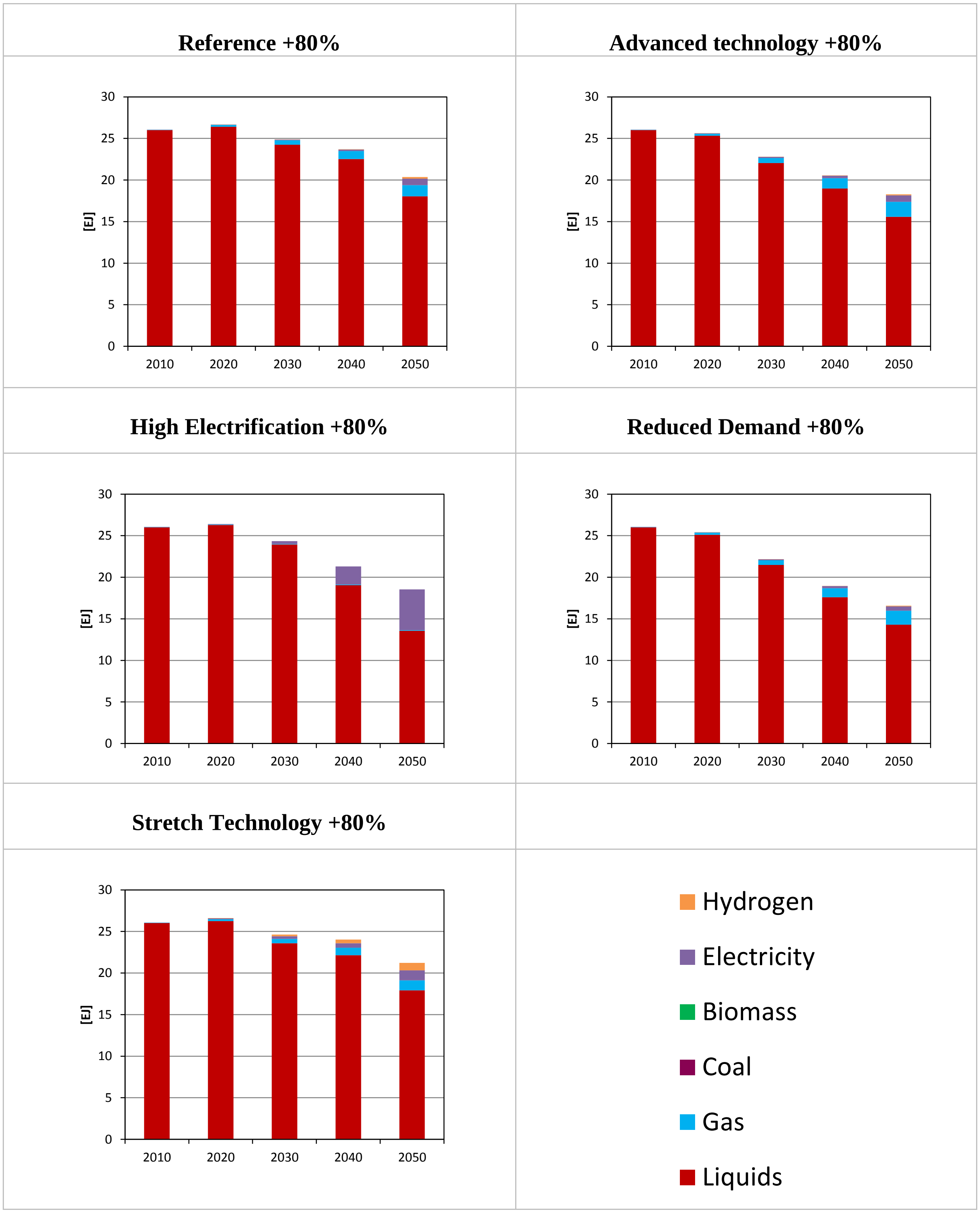


Figure A5: Transportation final energy consumption by fuel

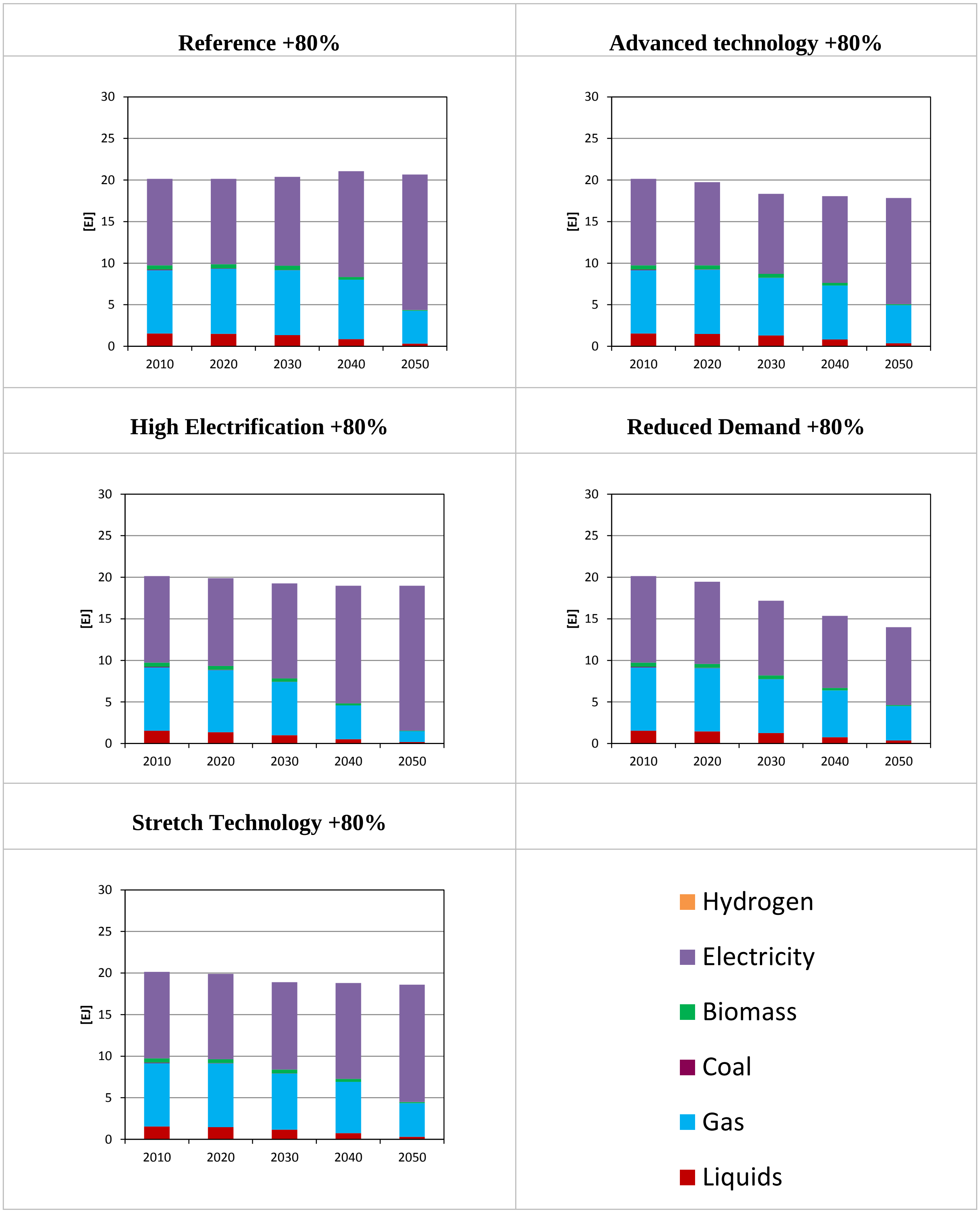
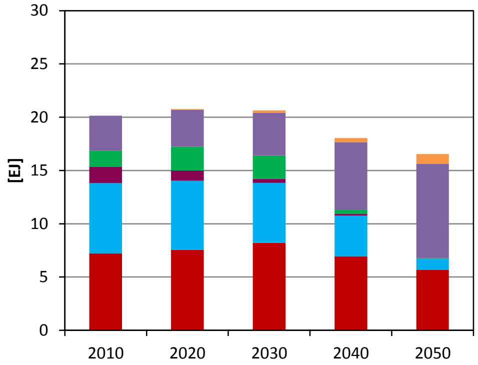
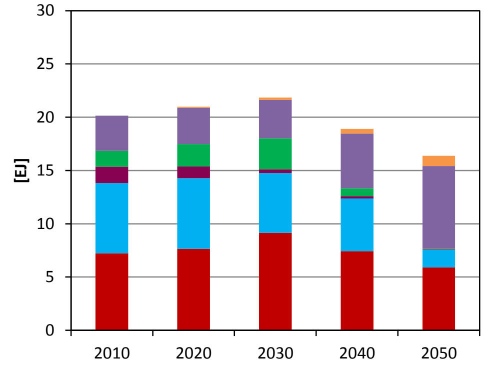


Figure A6: Buildings final energy consumption by fuel

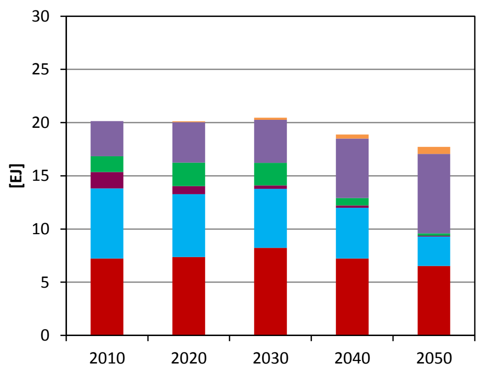
Reference +80%



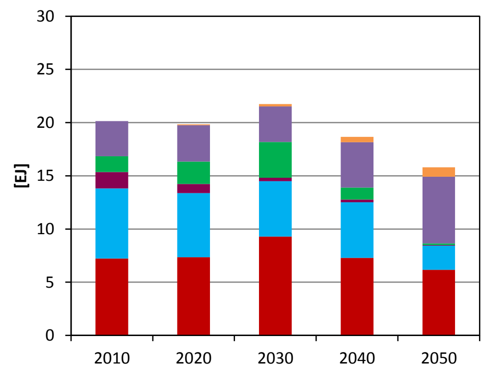
Advanced technology +80%



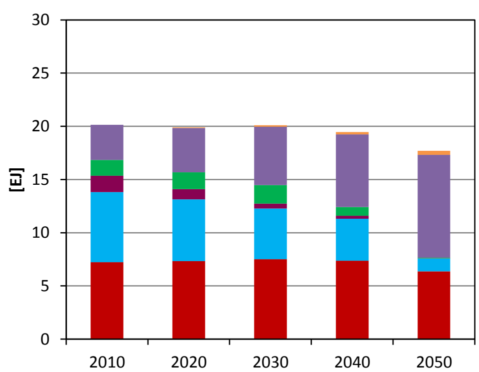
High Electrification +80%



Reduced Demand +80%



Stretch Technology +80%



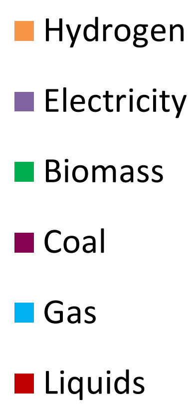


Figure A7: Industrial final energy consumption by fuel

Appendix A: Tables

Table A1: Electric power sector capital cost assumptions, *Reference* and *Reference +80%* scenarios (2010$/kW)

Technology	**2020**	**2035**	**2050**
Biomass (conv)	3950	3818	3702
Biomass (IGCC)	5745	5180	4819
Biomass (conv CCUS)	7317	6568	6168
Biomass (IGCC CCUS)	8337	7298	6719
Coal (conv pul)	2337	2242	2196
Coal (IGCC)	3060	2855	2769
Coal (conv pul CCUS)	5503	4925	4618
Coal (IGCC CCUS)	4020	3607	3448
Gas (CC)	859	824	807
Gas (steam/CT)	912	875	857
Gas (CC CCUS)	1864	1678	1606
Refined liquids (steam/CT)	742	717	694
Refined liquids (CC)	1036	1004	972
Refined liquids (CC CCUS)	2356	2079	1937
Gen II LWR (Nuclear)	5500	5500	5500
Gen III (Nuclear)	4400	4044	3901
CSP	3415	3077	2946
CSP with storage	7429	6329	5770
PV	1856	1535	1514
PV with storage	4212	3799	3534
Wind	1662	1526	1481
Wind with storage	5555	5006	4661
Rooftop PV	4499	4057	3776
Geothermal	4347	4199	4073

Table A2: Electric power sector fixed and variable O&M assumptions, *Reference* and *Reference +80%* scenarios (2010$)

Technology	Parameter	Units	2020	2035	2050
Biomass (conv)	Fixed	$/kW	93.8	90.7	88.0
	Variable	$/MWh	9.9	9.6	9.3
Biomass (IGCC)	Fixed	$/kW	134.1	120.8	112.5
	Variable	$/MWh	14.4	12.9	12.0
Biomass (conv CCUS)	Fixed	$/kW	113.0	106.3	102.0
	Variable	$/MWh	12.9	12.0	11.5
Biomass (IGCC CCUS)	Fixed	$/kW	160.1	142.8	132.1
	Variable	$/MWh	17.0	15.1	14.0
Coal (conv pul)	Fixed	$/kW	24.7	23.9	23.1
	Variable	$/MWh	3.9	3.8	3.7
Coal (IGCC)	Fixed	$/kW	33.5	30.2	28.1
	Variable	$/MWh	6.2	5.6	5.2
Coal (conv pul CCUS)	Fixed	$/kW	47.5	42.4	39.8
	Variable	$/MWh	7.6	6.8	6.4
Coal (IGCC CCUS)	Fixed	$/kW	65.4	56.2	51.4
	Variable	$/MWh	9.4	8.2	7.6
Gas (CC)	Fixed	$/kW	9.9	9.6	9.3
	Variable	$/MWh	3.5	3.4	3.2
Gas (steam/CT)	Fixed	$/kW	5.9	5.7	5.6
	Variable	$/MWh	9.9	9.6	9.3
Gas (CC CCUS)	Fixed	$/kW	19.0	17.0	15.9
	Variable	$/MWh	6.7	5.9	5.6
Refined liquids (steam/CT)	Fixed	$/kW	5.9	5.7	5.6
	Variable	$/MWh	9.9	9.6	9.3
Refined liquids (CC)	Fixed	$/kW	9.9	9.6	9.3
	Variable	$/MWh	3.5	3.4	3.2
Refined liquids (CC CCUS)	Fixed	$/kW	22.4	19.8	18.5
	Variable	$/MWh	7.8	6.9	6.5
Gen II LWR (Nuclear)	Fixed	$/kW	105.0	105.0	105.0
	Variable	$/MWh	2.2	2.2	2.2
Gen III (Nuclear)	Fixed	$/kW	93.8	90.7	88.0
	Variable	$/MWh	2.0	1.9	1.8
CSP	Fixed	$/kW	50.0	40.9	36.7
CSP with storage	Fixed	$/kW	59.6	49.5	44.7
PV	Fixed	$/kW	38.3	34.5	32.2
PV with storage	Fixed	$/kW	46.0	41.4	38.6
Wind	Fixed	$/kW	47.9	43.2	40.2
Wind with storage	Fixed	$/kW	57.5	51.8	48.2
Rooftop PV	Fixed	$/kW	57.5	51.8	48.2
Geothermal	Fixed	$/kW	98.8	95.4	92.6

Table A3: Electric power sector efficiency and capacity factor assumptions, all scenarios[75]

Technology	Efficiency				Capacity Factor
	2020	2035	2050		
Biomass (conv)	28%	31%	33%		0.85
Biomass (IGCC)	34%	38%	41%		0.8
Biomass (conv CCUS)	23%	30%	34%		0.8
Biomass (IGCC CCUS)	30%	37%	41%		0.8
Coal (conv pul)	41%	44%	47%		0.85
Coal (IGCC)	43%	47%	51%		0.8
Coal (conv pul CCUS)	34%	42%	48%		0.8
Coal (IGCC CCUS)	37%	45%	50%		0.8
Gas (CC)	58%	61%	63%		0.8
Gas (steam/CT)	39%	41%	43%		0.85
Gas (CC CCUS)	50%	58%	63%		0.8
Refined liquids (steam/CT)	37%	40%	42%		0.8
Refined liquids (CC)	57%	60%	63%		0.85
Refined liquids (CC CCUS)	47%	56%	62%		0.8
Gen II LWR (Nuclear)	33%	33%	33%		0.9
Gen III (Nuclear)	33%	33%	33%		0.9
Geothermal	10%	10%	10%		0.9

[75] Capacity factor assumptions for wind (with and without dedicated storage) and rooftop PV technologies are embodied in the resource curves. Units deployed earlier in optimal locations are assumed to have higher capacity factors, while subsequent units in less optimal locations assumed to have lower capacity factors. Thus, capacity factor assumptions for these technologies vary with deployment. In addition, since wind and rooftop PV resource curves vary by state, capacity factor assumptions also vary by state. Capacity factor assumptions for utility scale PV and CSP technologies do not vary with deployment, but vary by state. Capacity factors for PV and CSP technologies with dedicated storage do not vary with deployment, vary by state and are higher than the intermittent counterparts.

Table A4: Residential buildings sector technology cost assumptions, *Reference and Reference +80%* scenarios (2010$/GJ)

Service	Technology	2005	2020	2035	2050
Heating	Wood furnace	4.4	4.2	4.2	4.1
	Coal furnace	4.4	4.2	4.2	4.1
	Gas furnace	7.3	7.3	7.3	7.3
	Gas furnace hi-eff	11.3	11.3	11.3	11.3
	Electric furnace	4.2	4.2	4.2	4.2
	Electric heat pump	6.3	6.5	7.0	7.2
	Fuel furnace	11.2	12.7	12.7	12.7
	Fuel furnace hi-eff	18.7	18.7	18.7	18.7
Cooling	Air conditioning	17.8	17.8	17.8	17.8
	Air conditioning hi-eff	43.3	43.3	43.3	43.3
Water Heating	Gas	31.8	32.0	32.0	32.0
	Gas hi-eff	53.6	53.6	53.6	53.6
	Electric resistance	17.8	17.8	17.8	17.8
	Electric resistance hi-eff	21.1	21.1	21.1	21.1
	Electric heat pump	56.9	54.0	54.0	54.0
	Fuel	31.8	32.0	32.0	32.0
	Fuel hi-eff	53.6	53.6	53.6	53.6
Lighting	Incandescent	0.5	2.4	2.4	2.4
	Fluorescent	0.79	0.59	0.57	0.56
	Solid state	13.8	0.81	0.49	0.49
Kitchen appliances	Refrigerator	29.2	32.1	32.1	32.1
	Refrigerator hi-eff	29.2	39.4	39.4	39.4
	Freezer	51.4	58.0	58.0	58.0
	Freezer hi-eff	58.0	61.2	61.2	61.2
	Dishwasher	0.60	0.60	0.60	0.60
	Dishwasher hi-eff	0.66	0.66	0.66	0.66
	Electric oven	41.8	41.8	41.8	41.8
	Gas oven	41.8	41.8	41.8	41.8
	Gas oven hi-eff	47.8	47.8	47.8	47.8
	LPG oven	41.8	41.8	41.8	41.8
	LPG oven hi-eff	47.8	47.8	47.8	47.8
Clothes appliances	Electric clothes dryer	0.09	0.12	0.12	0.12
	Electric clothes dryer hi-eff	0.11	0.15	0.15	0.15
	Gas clothes dryer	0.09	0.10	0.10	0.10
	Clothes washer	0.37	0.40	0.40	0.40
	Clothes washer hi-eff	0.38	0.55	0.55	0.55
Other	Television	64.6	64.5	64.5	64.5
	Computer	64.6	64.5	64.5	64.5
	Furnace fan	64.6	64.5	64.5	64.5
	Gas other	64.5	62.6	61.7	60.5
	Electric other	64.6	64.5	64.5	64.5
	Liquids other	64.5	62.6	61.7	60.5

Table A5: Commercial buildings sector, technology cost assumptions, *Reference* and *Reference +80%* scenarios (2010$/GJ)

Service	Technology	2005	2020	2035	2050
Heating	Wood furnace	4.3	4.2	4.2	4.1
	Coal furnace	4.4	4.2	4.2	4.1
	Gas furnace	3.3	3.8	3.8	3.8
	Gas furnace hi-eff	5.6	5.6	5.6	5.6
	Electric furnace	5.4	6.2	6.2	6.2
	Electric heat pump	22.1	22.1	22.1	22.1
	Fuel furnace	3.6	3.7	3.7	3.7
Cooling	Gas cooling	49.4	49.4	49.4	49.4
	Air conditioning	5.4	7.4	7.4	7.4
	Air conditioning hi-eff	13.1	13.1	13.1	13.1
Water Heating	Gas	4.1	4.1	4.1	4.1
	Electric resistance	4.6	4.6	4.6	4.6
	Electric heat pump	45.3	40.9	40.9	40.9
	Fuel	7.1	9.7	9.7	9.7
Ventilation	Ventilation	166.5	175.4	175.4	175.4
	Ventilation hi-eff	235.2	235.2	235.2	235.2
Lighting	Solid state	23.8	2.3	1.7	1.7
	Incandescent	6.4	5.5	5.2	5.2
	Fluorescent	1.2	1.2	1.1	1.1
Kitchen Appliances	Gas range stove	7.9	7.9	7.9	7.9
	Gas range hi-eff stove	10.6	10.6	10.6	10.6
	Electric range stove	10.9	10.9	10.9	10.9
	Electric range hi-eff stove	12.6	12.6	12.6	12.6
	Refrigeration	138.5	144.5	144.5	144.5
	Refrigeration hi-eff	138.5	158.9	158.9	158.9
Other	Office equipment	142.6	138.4	136.3	133.6
	Gas other	64.6	62.6	61.7	60.5
	Electricity other	129.3	125.4	123.6	121.2
	Liquids other	64.5	62.6	61.7	60.5

Table A6: Residential buildings sector, technology efficiency assumptions, *Reference* and *Reference +80%* scenarios

Service	Technology	Units	2005	2020	2035	2050
Heating	Wood furnace	Out/in	0.40	0.40	0.40	0.40
	Coal furnace	Out/in	0.40	0.40	0.40	0.40
	Gas furnace	Out/in	0.78	0.80	0.80	0.80
	Gas furnace hi-eff	Out/in	0.98	0.98	0.98	0.98
	Electric Heat Pump	Out/in	2.26	2.67	2.75	2.77
	Electric furnace	Out/in	0.99	0.99	0.99	0.99
	Fuel furnace	Out/in	0.80	0.83	0.83	0.83
	Fuel furnace hi-eff	Out/in	0.97	0.97	0.97	0.97
Cooling	Air Conditioning	Out/in	3.04	3.81	3.81	3.81
	Air conditioning hi-eff	Out/in	7.03	7.03	7.03	7.03
Water Heating	Gas	Out/in	0.59	0.62	0.62	0.62
	Gas hi-eff	Out/in	0.82	0.82	0.82	0.82
	Electric resistance	Out/in	0.89	0.90	0.90	0.90
	Electric resistance hi-eff	Out/in	0.95	0.96	0.96	0.96
	Electric heat pump	Out/in	2.00	2.30	2.45	2.50
	Fuel	Out/in	0.59	0.62	0.62	0.62
	Fuel hi-eff	Out/in	0.82	0.82	0.82	0.82
Lighting	Incandescent	mil lumen-hours/GJ	4.03	5.50	5.50	5.50
	Fluorescent	mil lumen-hours/GJ	18.67	19.17	19.64	20.14
	Solid state	mil lumen-hours/GJ	12.22	43.61	56.11	56.11
Kitchen appliances	Refrigerator	Out/in	1.92	2.53	2.53	2.53
	Refrigerator hi-eff	Out/in	2.00	2.97	2.97	2.97
	Freezer	Out/in	1.00	1.39	1.39	1.39
	Freezer hi-eff	Out/in	1.39	1.46	1.46	1.46
	Dishwasher	cycles/GJ	194.44	194.44	194.44	194.44
	Dishwasher hi-eff	cycles/GJ	333.33	333.33	333.33	333.33
	Electric oven	Out/in	0.62	0.621	0.62	0.62
	Gas oven	Out/in	0.40	0.40	0.40	0.40
	Gas oven hi-eff	Out/in	0.42	0.42	0.42	0.42
	LPG oven	Out/in	0.40	0.40	0.40	0.40
	LPG oven hi-eff	Out/in	0.42	0.42	0.42	0.42
Clothes appliances	Electric clothes dryer	kg/GJ	447.69	480.48	480.48	480.48
	Electric clothes dryer hi-eff	kg/GJ	480.48	683.52	683.52	683.52
	Gas clothes dryer	kg/GJ	395.98	416.17	416.17	416.17
	Clothes washer	cycles/GJ	1262.6	2777.8	2777.8	2777.8

	Clothes washer hi-eff	cycles/GJ	2525.3	3086.4	3086.4	3086.4
Other	Television	Indexed to 1 in 2005	1.00	1.25	1.35	1.35
	Computer	Indexed to 1 in 2005	1.00	1.50	3.00	3.80
	Furnace fan	Indexed to 1 in 2005	1.00	1.33	1.83	2.00
	Gas other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00
	Electricity other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00
	Liquids other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00

Table A7: Commercial Buildings sector, technology efficiency assumptions, *Reference* and *Reference +80%* scenarios

Service	Technology	Units	2005	2020	2035	2050
Heating	Wood furnace	Out/in	0.65	0.65	0.65	0.65
	Coal furnace	Out/in	0.65	0.65	0.65	0.65
	Gas furnace	Out/in	0.76	0.78	0.78	0.78
	Gas furnace hi-eff	Out/in	0.88	0.88	0.89	0.89
	Electric heat pump	Out/in	3.30	3.30	3.30	3.30
	Fuel furnace	Out/in	0.79	0.80	0.80	0.80
Cooling	Gas cooling	Out/in	0.87	0.98	1.05	1.08
	Air conditioning	Out/in	2.87	3.22	3.22	3.22
	Air conditioning hi-eff	Out/in	5.80	6.06	6.28	6.28
Water heating	Gas	Out/in	0.79	0.80	0.80	0.80
	Gas hi-eff	Out/in	0.99	0.99	0.99	0.99
	Electric resistance	Out/in	0.98	0.98	0.98	0.98
	Electric HP	Out/in	2.45	2.45	2.45	2.45
	Fuel	Out/in	0.79	0.80	0.80	0.80
Ventilation	Ventilation	Million m3/GJ	0.61	0.73	0.77	0.82
	Ventilation hi-eff	Million m3/GJ	2.42	2.57	2.74	2.93
Lighting	Incandescent	mil lumen-hours/GJ	3.75	5.65	5.93	5.93
	Fluorescent	mil lumen-hours/GJ	19.33	19.81	20.13	20.13
	Solid state	mil lumen-hours/GJ	17.50	47.22	56.11	56.11
Kitchen Appliances	Gas range stove	Out/in	0.45	0.45	0.45	0.45
	Gas range hi-eff stove	Out/in	0.60	0.60	0.60	0.60
	Electric range stove	Out/in	0.70	0.70	0.70	0.70
	Electric range hi-eff stove	Out/in	0.80	0.80	0.80	0.80
	Refrigeration	Out/in	2.06	3.32	3.32	3.32
	Refrigeration hi-eff	Out/in	3.76	4.12	4.12	4.12
Other	Office equipment	Indexed to 1 in 2005	1.00	1.45	1.45	1.45
	Gas other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00
	Electricity other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00
	Liquids other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00

Table A8: Transportation sector, electric and conventional (liquid-fueled) freight vehicle assumptions, *Reference* and *Reference +80%* scenarios

Parameter	Class	Technology	2005	2020	2035	2050
CAPEX and non-fuel OPEX (2010$/vkt)	Truck (0-2.7t)	Liquids	1.14	1.14	1.14	1.14
	Truck (0-2.7t)	BEV	3.04	1.74	1.65	1.56
	Truck (2.7-4.5t)	Liquids	1.25	1.25	1.25	1.25
	Truck (2.7-4.5t)	BEV	3.31	1.89	1.79	1.70
	Truck (4.5-12t)	Liquids	1.35	1.35	1.35	1.35
	Truck (4.5-12t)	BEV	3.60	2.05	1.95	1.84
	Truck (>12t)	Liquids	1.37	1.37	1.37	1.37
	Truck (>12t)	BEV	3.63	2.07	1.97	1.86
Intensity (MJ/vkm)	Truck (0-2.7t)	Liquids	4.74	3.45	2.93	2.81
	Truck (0-2.7t)	BEV	1.42	1.40	1.38	1.36
	Truck (2.7-4.5t)	Liquids	5.36	4.61	4.18	4.02
	Truck (2.7-4.5t)	BEV	1.61	1.58	1.56	1.54
	Truck (4.5-12t)	Liquids	10.79	9.34	8.48	8.14
	Truck (4.5-12t)	BEV	3.24	3.19	3.14	3.10
	Truck (>12t)	Liquids	13.32	11.53	10.46	10.05
	Truck (>12t)	BEV	4.00	3.94	3.88	3.82
Load factor (tons/vehicle)	Truck (0-2.7t)	Liquids	0.27	0.27	0.27	0.27
	Truck (0-2.7t)	BEV	Same as liquids			
	Truck (2.7-4.5t)	Liquids	1.01	1.01	1.01	1.01
	Truck (2.7-4.5t)	BEV	Same as liquids			
	Truck (4.5-12t)	Liquids	3.60	3.60	3.60	3.60
	Truck (4.5-12t)	BEV	Same as liquids			
	Truck (>12t)	Liquids	4.16	4.16	4.16	4.16
	Truck (>12t)	BEV	Same as liquids			

Table A9: Transportation sector, selected light and medium-duty vehicle capital cost and intensity assumptions, *Reference* and *Reference +80%* scenarios

Parameter	Class	Technology	2005	2020	2035	2050
Capital costs (purchase) (2010$/ vehicle)	Compact Car	Liquids	17747	17747	17747	17747
		Hybrid Liquids	20996	19696	18884	18803
		BEV	48826	28817	19324	19158
	Midsize Car	Liquids	25634	25634	25634.3	25634
		Hybrid Liquids	29606	28017	27024.2	26925
		BEV	64951	37950	36093	34235
	Large Car	Liquids	33522	33522	33522	33522
		Hybrid Liquids	38817	35905	34912	34712
		BEV	88212	50856	48286	45716
	Light Truck and SUV	Liquids	34508	34508	34508	34508
		Hybrid Liquids	39923	37757	36403	36268
		BEV	91687	52682	49999	47315
Intensity (MJ/vkm)	Compact Car	Liquids	2.914	2.176	1.672	1.655
		Hybrid Liquids	2.186	1.690	1.311	1.298
		BEV	0.780	0.772	0.764	0.756
	Midsize Car	Liquids	3.728	2.784	2.139	2.118
		Hybrid Liquids	2.797	2.162	1.677	1.660
		BEV	1.003	0.993	0.982	0.972
	Large Car	Liquids	3.868	2.888	2.220	2.197
		Hybrid Liquids	2.902	2.244	1.740	1.722
		BEV	1.046	1.035	1.024	1.014
	Light Truck and SUV	Liquids	4.039	3.016	2.318	2.294
		Hybrid Liquids	3.030	2.343	1.817	1.798
		BEV	1.095	1.083	1.072	1.061
Load factor (persons/vehicle)	Compact Car	Liquids	1.58	1.58	1.58	1.58
		Hybrid Liquids	1.58	1.58	1.58	1.58
		BEV	1.58	1.58	1.58	1.58
	Midsize Car	Liquids	1.58	1.58	1.58	1.58
		Hybrid Liquids	1.58	1.58	1.58	1.58
		BEV	1.58	1.58	1.58	1.58
	Large Car	Liquids	1.58	1.58	1.58	1.58
		Hybrid Liquids	1.58	1.58	1.58	1.58
		BEV	1.58	1.58	1.58	1.58
	Light Truck and SUV	Liquids	1.734	1.734	1.734	1.734
		Hybrid Liquids	1.734	1.734	1.734	1.734
		BEV	1.734	1.734	1.734	1.734

Table A10: Industrial sector, selected technology efficiency assumptions, *Reference* and *Reference +80%* scenarios (Indexed to 1 in 2005)

Technology	**2005**	**2020**	**2035**	**2050**
Biomass	1.000	0.997	1.006	1.014
Coal	1.000	1.030	1.042	1.051
Electricity	1.000	1.015	1.030	1.046
Gas	1.000	1.016	1.033	1.048
Hydrogen	1.000	1.000	1.015	1.030
Refined liquids	1.000	1.019	1.037	1.052

Table A11: Tax credit assumptions for low- and zero-carbon technologies, *Reference* and *Reference +80%* scenarios

	Production Tax Credit (2010$/kWh)									
Technology	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**Future Years**
Wind – Onshore	$0.021	$0.021	$0.021	$0.021	$0.017	$0.013	$0.008	-	-	-
Geothermal	$0.021	$0.021	$0.021	$0.021	$0.021	-	-	-	-	-
Landfill Gas	$0.011	$0.011	$0.011	$0.011	-	-	-	-	-	-
Hydro	$0.011	$0.011	$0.011	$0.011	$0.011	-	-	-	-	-

	Investment Tax Credit (% of overnight capital cost)									
Technology	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**Future Years**
Utility PV	30%	30%	30%	30%	30%	30%	26%	22%	10%	10%
CSP	30%	30%	30%	30%	30%	30%	30%	26%	22%	10%
Wind – Offshore	30%	30%	30%	30%	30%	24%	18%	12%	0%	0%
Biomass	30%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fuel Cells	30%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Resid. PV	30%	30%	30%	30%	26%	22%	0%	0%	0%	0%
Comm. PV	30%	30%	30%	30%	26%	22%	10%	10%	10%	10%

Table A12: Electric power sector, capital cost assumptions, *Advanced Technology +80%*, and *Stretch Technology +80%* scenarios (2010$/kW)[76,77,78]

	Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%				Stretch Technology +80%			
	2005	**2020**	**2035**	**2050**	**2005**	**2020**	**2035**	**2050**
Coal (IGCC CCUS)	4315	4310	3464	3103	4315	4310	3129	3103
Gas (CC)	Same as reference				856	846	817	807
Gas (CC CCUS)	1931	1766	1577	1466	1931	1837	1559	1466
Gen III (Nuclear)	4400	3952	3275	2710	4400	3898	2394	1892
CSP	3442	4278	2470	2343	3442	3192	2443	2193
PV	2053	1247	684	641	2053	1247	623	560
Wind	1682	1331	1200	1201	1682	1215	538	526

[76] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.

[77] All technologies not presented are assumed to be the same as the *Reference* scenario

[78] Where *Stretch Technology +80%* parameters are not presented, they are assumed to be the same as the *Advanced Technology +80%* scenario

Table A13: Electric power sector, fixed and variable O&M cost assumptions, *Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%* and *Stretch Technology +80%* scenarios (2010$)[79,80,81]

			Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%					Stretch Technology +80%			
Technology	**Parameter**	**Units**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Gas (CC)	Fixed	$/kW	Same as reference					30.1	30.1	25.9	25.9
	Variable	$/MWh	Same as reference					6.4	6.4	5.5	5.5
Coal (IGCC CCUS)	Fixed	$/kW	42.5	42.5	36.3	34.0		42.5	42.5	34.0	34.0
	Variable	$/MWh	14.2	14.2	12.1	11.3		14.2	14.2	11.3	11.3
Gas (CC CCUS)	Fixed	$/kW	30.0	30.0	26.9	25.8		30.1	30.1	25.9	25.9
	Variable	$/MWh	6.4	6.4	5.7	5.5		6.4	6.4	5.5	5.5
Gen III (Nuclear)	Fixed	$/kW	80.3	80.3	80.3	80.3		58.0	58.0	58.0	58.0
CSP	Fixed	$/kW	56.7	52.1	37.2	37.2		42.5	42.5	34.0	34.0
PV	Fixed	$/kW	17.4	9.3	9.3	9.3		17.5	9.3	4.9	4.4
Wind	Fixed	$/kW	47.3	44.1	38.9	37.6		50.3	36.6	33.1	32.0

[79] PNNL modified inputs used for a separate analysis published by DOE (“Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy”, January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.

[80] All technologies not presented are assumed to be the same as the *Reference* scenario.

[81] Where *Stretch Technology +80%* parameters are not presented, they are assumed to be the same as the *Advanced Technology +80%* scenario.

Table A14: Residential buildings sector, technology cost assumptions, *Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%* scenarios (2010$/GJ) [82,83]

Service	Technology	2005	2020	2035	2050
Heating	Gas furnace	7.3	9.8	11.4	11.4
	Electric heat pump	6.1	6.1	7.0	7.2
	Fuel furnace	11.2	15.0	15.0	15.0
Cooling	Air conditioning	17.8	22.0	24.5	24.5
Water Heating	Gas	31.8	32.0	53.6	53.6
	Gas hi-eff	87.0	49.9	49.9	49.9
	Electric resistance	17.8	18.5	18.5	18.5
	Fuel	31.9	42.2	53.6	53.6
	Fuel hi-eff	87.0	88.2	83.2	81.5
Kitchen appliances	Refrigerator	29.2	37.8	41.1	41.1
	Refrigerator hi-eff	29.2	45.2	45.2	45.2
	Freezer	51.4	61.2	63.2	63.2
	Freezer hi-eff	58.0	94.2	94.2	94.2
	Dishwasher	0.60	0.60	0.65	0.65
	Electric oven	71.7	71.7	71.7	71.7
Clothes appliances	Electric clothes dryer	0.09	0.12	0.15	0.15
	Gas clothes dryer	0.09	0.10	0.13	0.13
	Clothes washer	0.37	0.40	0.55	0.55

[82] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.
[83] All technologies not presented are assumed to be the same as the *Reference* scenario.

Table A15: Commercial buildings sector, technology cost assumptions, *Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%* scenarios (2010$/GJ)[84,85]

Service	Technology	2005	2020	2035	2050
Heating	Gas furnace	3.4	3.5	4.0	4.0
	Electric furnace	5.4	5.4	5.4	5.4
	Electric heat pump	22.1	27.5	27.5	27.5
	Fuel furnace	3.6	3.8	3.8	3.8
Cooling	Air conditioning	5.4	7.8	10.9	10.9
Water Heating	Gas	4.1	4.6	4.6	4.6
	Electric resistance	4.6	4.6	38.5	38.5
	Electric heat pump	40.9	38.7	38.7	38.7
Lighting	Solid state	23.8	2.5	2.0	2.0
Kitchen appliances	Refrigeration	138.5	140.3	140.3	140.3
	Refrigeration hi-eff	156.8	156.9	156.9	156.9

[84] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.
[85] All technologies not presented are assumed to be the same as the *Reference* scenario.

Table A16: Residential buildings sector, technology efficiency assumptions, Advanced Technology +80%, High Electrification +80%, Reduced Demand +80% scenario (2010$/GJ)[86,87]

Service	Technology	Units	2005	2020	2035	2050
Heating	Gas furnace	Out/in	0.78	0.92	0.98	0.98
	Electric Heat Pump	Out/in	2.26	2.45	2.74	2.77
	Fuel furnace	Out/in	0.80	0.85	0.86	0.86
Cooling	Air Conditioning	Out/in	3.04	4.54	4.84	4.84
Water Heating	Gas	Out/in	0.59	0.62	0.82	0.82
	Gas hi-eff	Out/in	0.80	1.20	1.20	1.20
	Electric resistance	Out/in	0.89	0.95	0.95	0.95
	Fuel	Out/in	0.59	0.67	0.82	0.82
	Fuel hi-eff	Out/in	0.8	0.85	0.85	0.85
Kitchen appliances	Refrigerator	Out/in	1.92	2.87	3.10	3.10
	Refrigerator hi-eff	Out/in	2.00	5.13	5.13	5.13
	Freezer	Out/in	1.00	1.46	1.52	1.52
	Freezer hi-eff	Out/in	1.39	2.61	2.61	2.61
	Dishwasher	cycles/ GJ	194.44	194.44	202.78	202.78
Clothes appliances	Electric clothes dryer	kg/GJ	447.69	480.48	683.52	683.52
	Gas clothes dryer	kg/GJ	395.99	416.17	455.26	455.26
	Clothes washer	cycles/ GJ	1262.6	2777.8	3086.4	3086.4

[86] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.
[87] All technologies not presented are assumed to be the same as the *Reference* scenario.

Table A17: Commercial buildings sector, technology efficiency assumptions, *Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%* scenarios (2010$/GJ)[88, 89]

Service	Technology	Units	2005	2020	2035	2050
Heating	Gas furnace	Out/in	0.76	0.80	0.88	0.88
	Electric heat pump	Out/in	3.30	3.40	3.40	3.40
	Fuel furnace	Out/in	0.79	0.81	0.81	0.81
	Air conditioning	Out/in	2.87	3.37	3.81	3.81
Water heating	Gas	Out/in	0.79	0.99	0.99	0.99
	Electric resistance	Out/in	0.98	0.98	2.00	2.00
	Electric HP	Out/in	2.45	2.45	4.10	4.10
	Fuel	Out/in	0.79	0.80	0.80	0.80
Kitchen Appliances	Refrigeration	Out/in	2.06	2.65	2.65	2.65
	Refrigeration hi-eff	Out/in	3.32	5.41	5.41	5.41

[88] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.
[89] All technologies not presented are assumed to be the same as the *Reference* scenario.

Table A18: Buildings sector, selected technology efficiencies, Advanced Technology +80%, High Electrification +80%, Reduced Demand +80% and Stretch Technology +80% scenarios[90, 91]

			Advanced Technology +80%, High Electrification +80% , Reduced Demand +80%					Stretch Technology +80%			
Service	**Technology**	**Units**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Residential other	Other gas	Out/in	1.00	1.00	1.00	1.00		1.00	1.10	1.50	1.50
	Other electricity	Out/in	1.00	1.00	1.00	1.00		1.00	1.00	1.10	1.20
Commercial office	Office equipment, electricity	Out/in	1.00	1.45	1.45	1.45		1.00	1.50	1.66	1.66
Commercial other	Other electricity	Out/in	1.00	1.00	1.00	1.00		1.00	1.10	1.25	1.25

[90] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.
[91] All technologies not presented are assumed to be the same as the *Reference* scenario.

Table A19: Transportation sector, capital cost and intensity assumptions, Advanced Technology +80%, High Electrification +80%, Reduced Demand +80% and Stretch Technology +80% scenarios[92,93,94]

Parameter	Class	Technology	Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%					Stretch Technology +80%			
			2005	2020	2035	2050		2005	2020	2035	2050
Capital costs (infrastructure) (2010$/veh)	Compact Car	Hydrogen FCEV	4951	4951	4951	4951		4951	3301	0	0
	Midsize Car	Hydrogen FCEV	4951	4951	4951	4951		4951	3301	0	0
	Large Car	Hydrogen FCEV	4951	4951	4951	4951		4951	3301	0	0
	Light Truck and SUV	Hydrogen FCEV	4951	4951	4951	4951		4951	3301	0	0
Capital costs (other) (2010$/veh)	Compact Car	Hydrogen FCEV	8770	2104	2052	1988		8770	2151	1871	1844
	Midsize Car	Hydrogen FCEV	11424	2905	2840	2759		11424	2964	2611	2578
	Large Car	Hydrogen FCEV	15033	3508	3442	3361		15033	3927	3442	3399
	Light Truck and SUV	Hydrogen FCEV	15543	3943	3852	3741		15543	4026	3535	3490
Capital costs (purchase) (2010$/veh)	Compact Car	Liquids	17746	18986	18382	18321		17746	18986	18382	18321
		Hybrid Liquids	20996	21071	19560	19411		20996	21071	19560	19411
		BEV	48826	28817	19324	19158		48826	28817	19324	19158
		Hydrogen FCEV	97447	23384	22802	22090		97447	23896	20790	20499
	Midsize Car	Liquids	25634	30220	29283	29089		Same as *Advanced Technology*			
		Hybrid Liquids	29606	33030	30870	30554		Same as *Advanced Technology*			
		BEV	64951	45870	30784	30419		Same as *Advanced Technology*			
		Hydrogen FCEV	126943	32285	31552	30653		126943	32937	29007	28645
	Large Car	Liquids	33522	36032	37043	36926		Same as *Advanced Technology*			
		Hybrid Liquids	38817	38593	38579	38347		Same as *Advanced Technology*			
		BEV	88212	56943	38895	38674		Same as *Advanced Technology*			
		Hydrogen FCEV	167035	38977	38245	37345		167035	43642	38246	37768
	Light Truck and SUV	Liquids	34508	37964	37914	37899		Same as *Advanced Technology*			
		Hybrid Liquids	39923	41538	39997	39832		Same as *Advanced Technology*			

[92] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.

[93] The *High Electrification +80%* scenario includes a modification to assume zero share for hydrogen vehicles in the light-duty vehicle sector.

[94] All technologies not presented are assumed to be the same as the *Reference* scenario.

		BEV	91687	64840	42775	42325		Same as *Advanced Technology*			
		Hydrogen FCEV	172705	43815	42804	41568		172705	44729	39276	38783
Intensity (MJ/vkm)	Compact Car	Liquids	2.91	1.861	1.245	1.179		2.91	1.82	0.95	0.86
		Hybrid Liquids	2.19	1.446	0.976	0.924		2.19	1.41	0.75	0.67
	Midsize Car	Liquids	3.73	2.381	1.593	1.509		3.73	2.32	1.22	1.10
		Hybrid Liquids	2.80	1.850	1.249	1.183		2.80	1.81	0.96	0.86
	Large Car	Liquids	3.87	2.47	1.65	1.57		3.87	2.41	1.27	1.14
		Hybrid Liquids	2.90	1.92	1.30	1.23		2.90	1.87	0.99	0.90
	Light Truck and SUV	Liquids	4.04	2.58	1.73	1.63		4.04	2.42	1.32	1.19
		Hybrid Liquids	3.03	2.00	1.35	1.28		3.03	1.96	1.04	0.94
	Truck (0-2.7t)	Liquids	4.74	3.15	2.52	2.41		4.74	3.12	2.35	2.22
		Natural Gas	5.69	5.34	4.96	4.60			5.30	4.62	4.23
	Truck (2.7-4t)	Liquids	5.36	4.27	3.55	3.43		5.36	3.92	2.90	2.82
	Truck (4.5-12t)	Liquids	10.79	8.65	7.20	6.95		10.79	7.94	5.88	5.71
	Truck (>12t)	Liquids	13.32	10.67	8.88	8.58		13.32	9.80	7.26	7.05

Table A20: Selected industrial sector efficiencies, Advanced Technology +80%, High Electrification +80%, Reduced Demand +80% and Stretch Technology +80% scenarios (Indexed to 1 in 2005)[95]

Technology	Advanced Technology +80%					Stretch Technology +80%			
	2005	2020	2035	2050		2005	2020	2035	2050
Biomass	1.000	1.002	1.030	1.019		1.000	1.104	1.270	1.387
Coal	1.000	1.013	1.041	1.030		1.000	1.111	1.271	1.438
Electricity	1.000	1.008	1.101	1.156		1.000	1.123	1.315	1.415
Gas	1.000	1.008	1.057	1.110		1.000	1.105	1.263	1.434
Hydrogen	1.000	1.024	1.088	1.088		1.000	1.093	1.241	1.410
Refined liquids	1.000	1.009	1.059	1.112		1.000	1.101	1.251	1.440

[95] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.

Table A21: Shell Efficiency Trajectories under the Reference, Reference +80%, Advanced Technology +80%, High Electrification +80%, Reduced Demand +80% and Stretch Technology +80% scenarios (indexed to 1 in 2010)[96]

Scenario	2010	2020	2030	2040	2050
Reference	1	0.96	0.92	0.90	0.90
Reference +80%	1	0.96	0.92	0.90	0.90
Advanced Technology +80%, High Electrification +80%, Reduced Demand +80%	1	0.91	0.78	0.71	0.71
Stretch Technology +80%	1	0.91	0.78	0.68	0.68

[96] PNNL modified inputs used for a separate analysis published by DOE ("Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy", January 2017, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, accessed 18 January 2017), which focuses on the impacts of technology and policy on energy CO_2 emissions for use in the GCAM-USA model framework.

Table A22: Floor-Space Assumptions for the Residential and Commercial Sectors, *Reference*, *Reference +80%*, *Advanced Technology +80%*, *High Electrification +80%*, and *Reduced Demand +80%* and *Stretch Technology +80%* scenarios (billion square meters)

Scenario	Sector	2010	2020	2030	2040	2050
Reference, *Reference +80%*, *Advanced Technology +80%*, *High Electrification +80%*, *Stretch Technology +80%*	Residential	17.5	19.4	21.9	24.3	26.4
	Commercial	7.5	8.3	9.1	10.1	11.3
Reduced Demand +80%	Residential	17.5	19.1	20.4	20.4	20.4
	Commercial	7.5	8.2	8.4	8.4	8.4

Table A23: Light duty vehicle and medium and heavy duty vehicle transportation service demands under *Reference*, *Reference +80%*, *Advanced Technology +80%* and *Reduced Demand +80%* scenarios

Scenario	Sector	Units	2010	2020	2030	2040	2050
Reference	Light duty vehicle	Trillion passenger-km	6.5	7.5	8.6	9.5	10.2
	Medium and heavy duty vehicle	Trillion passenger-km	2.0	2.3	2.6	3.0	3.3
Reference + 80%	Light duty vehicle	Trillion passenger-km	6.5	7.5	8.5	9.1	9.0
	Medium and heavy duty vehicle	Trillion ton-km	2.0	2.3	2.6	2.9	2.9
Advanced technology + 80%	Light duty vehicle	Trillion passenger-km	6.5	7.4	8.5	9.3	9.6
	Medium and heavy duty vehicle	Trillion ton-km	2.0	2.2	2.4	2.7	2.9
Reduced Demand + 80%	Light duty vehicle	Trillion passenger-km	6.5	7.3	8.0	7.8	7.3
	Medium and heavy duty vehicle	Trillion ton-km	2.0	2.2	2.3	2.7	2.9

APPENDIX B: LOW CARBON FUTURES OF THE U.S. ENERGY SYSTEM WORKSHOP REPORT

I. INTRODUCTION

In 2009, and subsequently in 2014, the United States set greenhouse gas (GHG) emissions reduction targets in the range of 17 percent below 2005 levels by 2020 and 26 to 28 percent below 2005 levels by 2025. Both of these goals were intended to put the United States on a path towards significant decarbonization, achieving an 80 percent economy-wide reduction in GHG emissions by 2050. The U.S. commitments will require policies and technology deployment to transform the energy sector over the near and long term. To explore these options, the U.S. Department of Energy's Office of Energy Policy and Systems Analysis (EPSA) hosted a one-day workshop entitled "Low Carbon Futures of the U.S. Energy System" on January 14, 2016. This workshop focused on understanding possible pathways to achieving 80% economy-wide GHG emissions reductions by 2050.

The workshop agenda was centered on two key areas of discussion: (1) potential pathways for substantial GHG reductions in electricity generation and (2) how future end use demand for electricity might shape the scale of required electric power sector GHG emissions reductions. There were two primary goals for the workshop:

1. Identify a set of representative pathways (and elements of such pathways) towards an 80% economy-wide reduction in GHG emissions by 2050.
    - Provide insight into the composition of electricity generation and capacity, as well as the scope and scale of energy demand.
    - Are the proposed pathways meaningful and representative of the types of efforts needed to reach a low carbon energy future? If not, what changes should be made? Are any key elements missing or unnecessary elements present in these pathways?
2. Identify the key characteristics, challenges, opportunities, and requirements of different pathways.
    - What key developments and/or actions would be needed for the U.S. to embark on any of these pathways?
    - What are the key barriers to implementing such actions?
    - What are the potential opportunities embedded in the pathways?
    - Are the scales and rates of change implied in the pathways reasonable? Are they possible?

This report summarizes the content, outcomes, and key findings of the workshop. The material in this report does not represent consensus among the participants, but rather documents themes that emerged during the workshop.

II. PATHWAYS TOWARDS 80% ECONOMY-WIDE EMISSIONS REDUCTIONS

The literature includes numerous modeling studies that explore the nature of the transformations required in the energy system to reach a low carbon energy future.[1,2,3] These studies indicate that potential pathways to reaching a low carbon energy future require substantial GHG emissions reductions in the electric power sector over the next 35 years. A common finding in studies of 80% economy-wide GHG emissions reductions by 2050 is that more than 80% of all electricity generated in the United States must be provided by low-carbon sources by 2050. While these studies tend to include large reductions in GHG emissions from the electric power sector, they also suggest that there is a range of pathways that could lead to these reductions (Figure 1).

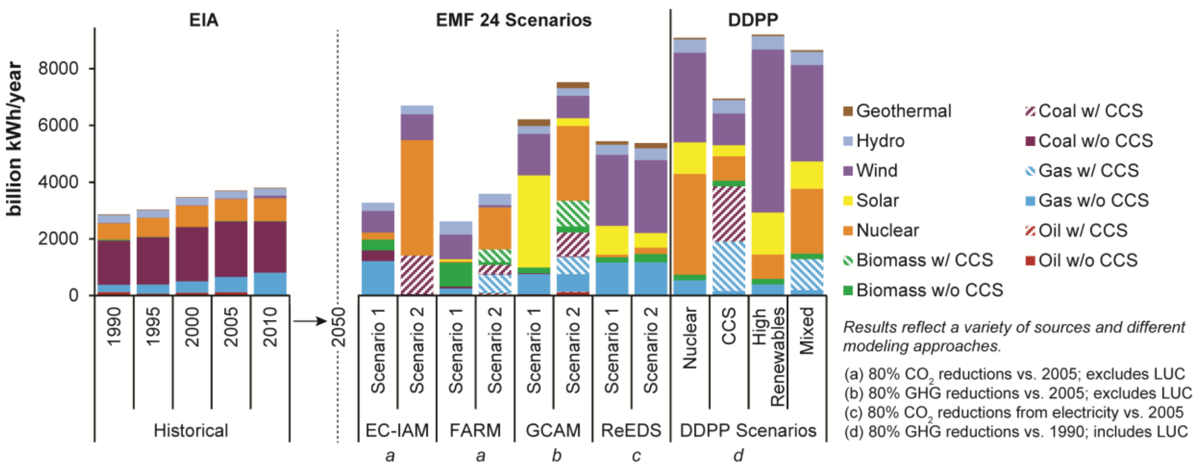


Figure 1. Electric Power Sector Transformations in 80% Economy-Wide GHG Emissions Reductions Scenarios. Comparing historical electricity generation to 2050 scenarios from the Energy Modeling Forum 24 (EMF 24) and the Deep Decarbonization Pathways Project.[4,5,6,7,8,9,10]

Studies have demonstrated the potential for a low carbon energy future relying predominantly on generation from renewable energy technologies such as wind and solar power; those relying predominantly on generation from nuclear and/or fossil energy with carbon dioxide capture and storage (CCS), often complemented with bioenergy with CCS; and those relying on generation from a mix of technologies. The studies also present varying levels of electricity demand: some studies anticipate high electricity demand futures that are driven by electrification in, for example, the transportation sector, while others explore scenarios with major demand reductions through increased efficiency across end-use sectors. This topic is explored further in Section III of the report.

Recognizing the projected share of GHG emissions reductions that will need to come from the electric power sector, a primary goal of the workshop was to solicit feedback on draft versions of four illustrative pathways towards 80% economy-wide GHG emissions reductions.

The meeting was also intended to serve as a forum for discussion about how these four pathways differ from one another and the key requirements and issues that might emerge in each.

At the workshop, participants reviewed and discussed the following four illustrative pathways, each of which was intended to describe one general category of electric power sector transformation that has been explored in the literature:

1. Mixed Generation
2. Mixed Generation with Lower Demand
3. High Renewable Energy
4. High Nuclear and CCS

As as framing concept for the meeting, the illustrative pathways were presented as depictions of how the share of technologies contributing to electricity generation production and capacity, and the scale of energy demand, would transform between the present time and 2050.

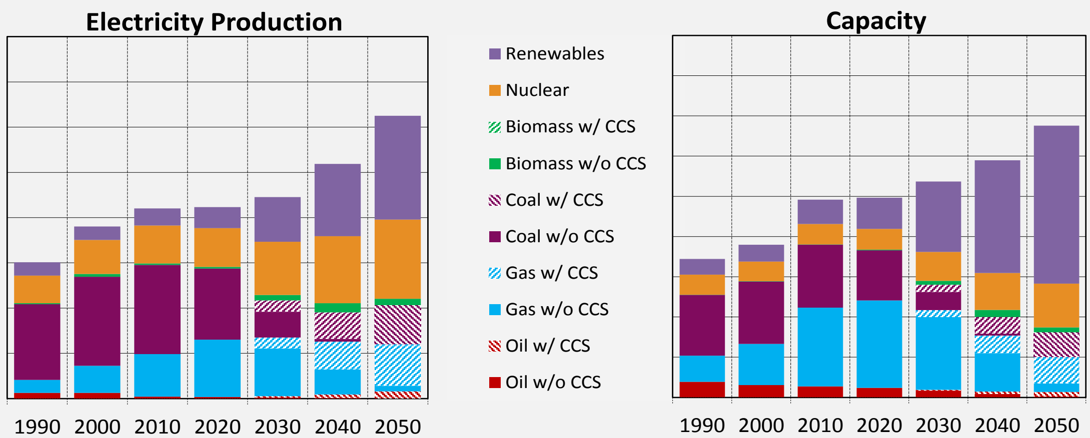
These four illustrative pathways were developed for EPSA by Pacific Northwest National Laboratory based on scenarios developed using a version of the Global Change Assessment Model with 50-state energy sector representation in the United States (GCAM-USA). Although the illustrative pathways for the workshop were constructed using a single model, their general characteristics should be seen as independent of any specific model. The general themes in each of the illustrative pathways were constructed in a sufficiently generic way so that the alternative representations could be created in other models. This is consistent with the fact that the illustrative pathways are intended to represent key categories of pathways that already exist in the literature.

All four illustrative pathways assume economy-wide U.S. GHG emissions reductions below 2005 levels of 17% in 2020 (corresponding to the United States' target in the range of 17%) and 27% in 2025 (corresponding to the U.S. Nationally Determined Contribution for the 2015 Conference of the Parties in Paris), as well as a linear path to 80% economy-wide U.S. GHG emissions reductions in 2050. For simplicity, GHG emissions reductions were obtained by employing an economy-wide constraint on carbon and allowing the model to select a mix of energy resources that could meet that constraint. As described below, technology assumptions vary in each pathway to illustrate a range of possible futures that rely on different generation mixes. In addition, the pathways assume consistent levels of climate mitigation policy in regions outside of the U.S.

FOUR ILLUSTRATIVE ELECTRIC POWER SECTOR PATHWAYS

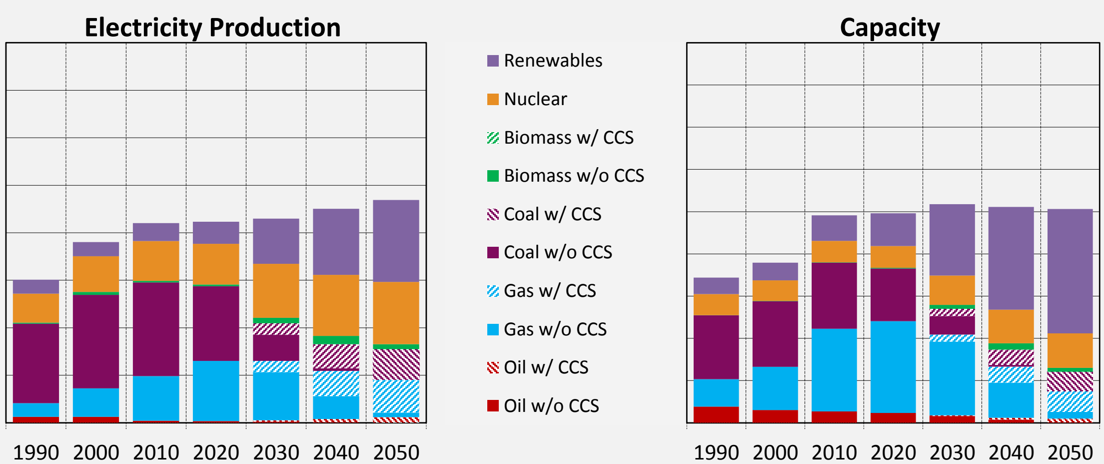
Mixed Generation

The Mixed Generation pathway is intended to represent a future in which all low-carbon electricity technologies are utilized in the electric power sector. 2050 technology deployment levels are roughly consistent with current perceptions of their technological readiness and future prospects. This means that electricity in 2050 is generated from a robust combination of hydroelectric power, wind power, solar power, nuclear power, and gas- and coal-fired power with CCS.



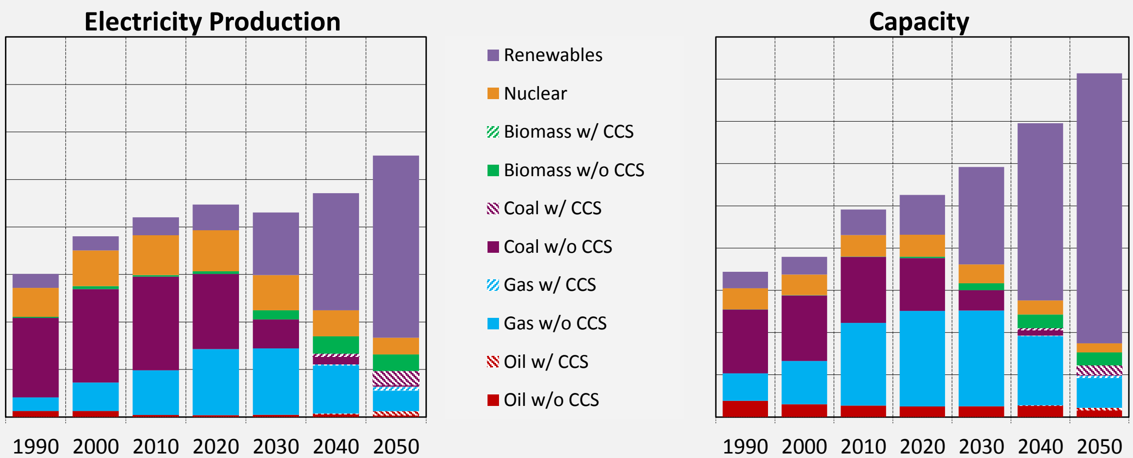
Mixed Generation Portfolio with Lower Demand

As a means to understanding the implications of lower energy demand growth—either through non-policy forces (e.g., economic instruments) or through explicit end use policies—a revised version of the Mixed Generation pathway was constructed in which energy demand by 2050 was 25% lower than in the Mixed Generation pathway. For simplicity, deployment levels of all low-carbon electricity sources were reduced by the same percentage in each year of the projection. Hence, while the level of generation and capacity is lower than in the Mixed Generation pathway, the proportions of individual technologies in the electricity generation mix are the same.



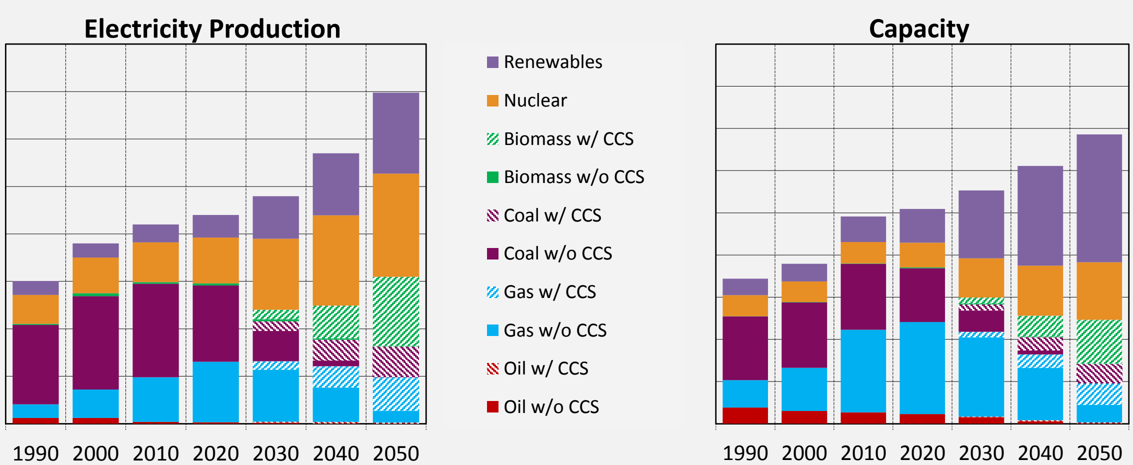
High Renewable Energy

The High Renewable Energy pathway is intended to represent a future in which GHG emissions reductions from the electric power sector are achieved largely through the addition of new wind and solar generation sources. It implicitly assumes that nuclear deployment is limited. CCS may be deployed in gas and coal-fired power plants, but the total share of CCS in the generation mix is well below the levels of wind and solar power generation.



High Nuclear and CCS

The High Nuclear and CCS pathway is intended to represent a future in which nuclear power, fossil fuel-fired power coupled with CCS, and bioenergy coupled with CCS (bioCCS) provide the backbone of electricity generation. The origin of this pathway can be viewed in two ways: first, as a pathway in which the deployment of renewable electricity generating sources is limited and other technologies must fill the gap, or second, as a pathway in which nuclear power and CCS technologies overcome a range of institutional constraints and prove to be the lower cost options for mitigation relative to renewable sources. For the purposes of the workshop, this is the only pathway that included bioCCS as a mitigation option in the electric power sector.



Discussion of the four illustrative pathways at the workshop was organized around four main questions:

1. Are these a meaningful and representative set of pathways? What adjustments should be made for these to serve effectively for use in long-term strategic planning?
2. What are the key barriers to undertaking any of these pathways?
3. What are the critical technological innovations and policies needed to achieve these 2040 and 2050 outcomes?
4. What actions, over what time frames, could the U.S. undertake to achieve these 2040 and 2050 outcomes?

To motivate this discussion, information was provided regarding the mix of variable and baseload power, as well as the scale and rate of deployment that might be expected for various electricity generating technologies under each of the four illustrative pathways. The information provided highlighted the fact that transitioning to a low-carbon energy future will require deployment rates for low-carbon electricity generating technologies above those in recent history. As an example, the historical peak deployment of nuclear generation occurred in the ten-year period from 1970–1980 when the U.S. added 44.8 GW of nuclear capacity. The illustrative high nuclear and CCS pathway presented at the workshop had a peak deployment of 101 GW of net summer capacity added in the 2020–2030 period.

Finally, to contextualize the role of the electric power sector within a broader energy-sector mitigation strategy, information was provided regarding overall electric power sector emissions over time from the four illustrative pathways. Consistent with the literature, electric power sector emissions are brought close to zero by 2050 in the two Mixed Generation pathways and in the High Renewable Energy pathway. In the High CCS and Nuclear pathway, the use of bioCCS technology allows the electric power sector to serve as a net sink for carbon dioxide; that is, the electric power sector would store more carbon dioxide emissions from the atmosphere than it produces.

III. THE FUTURE OF ENERGY DEMAND

The second major focus of the workshop explored energy demand in buildings, industry, and transportation. These three end-use sectors are important because they are themselves a significant source of direct GHG emissions (Figure 2), and because they set the scale for electric power sector demand (Figure 3). According to the relevant literature, both of these factors, not just energy efficiency, must be considered in potential pathways to a low-carbon future. For example, low-carbon scenarios in the literature indicate that the use of low-carbon fuels—such as bioenergy or low-carbon electricity—in end-use sectors may be needed to achieve deep emissions reductions.

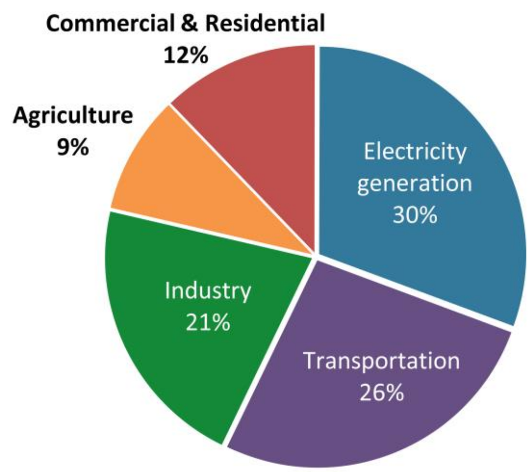


Figure 2. 2014 U.S. Greenhouse Gas Emissions by Sector[11]

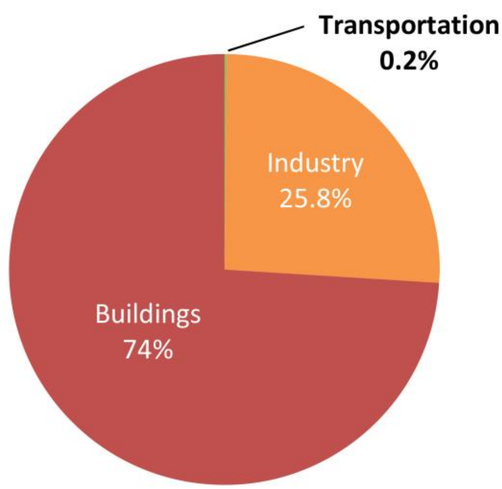


Figure 3. 2013 Electricity Consumption by End-Use Sector[12]

The evolution of energy use in end-use sectors directly influences the scale of low-carbon electricity deployment that will be needed to achieve 80% economy-wide GHG emissions reductions. Two countervailing forces influence this scale. The first is the potential to reduce energy demand through, for example, increased end-use efficiency. The second is the potential to increase the scope of electricity use in end-use sectors, which must be generated from low-carbon sources. Examples of electrification could include the increasing use of electric heat pumps, electric cars, and electric motors for mechanical drive applications.

In exploring these various energy demand issues, the workshop discussion was organized around four main questions:

1. What is a reasonable scale and rate of change for the combined future energy demand in the buildings, industrial, and transportation sectors?
2. How can we characterize the relationship between energy demand across these sectors?
3. How much can reductions in energy demand contribute to overall GHG emissions reductions?
4. Where are the opportunities for the largest GHG emissions reductions relative to upfront investments?

To help frame these discussions, an overview of the current character and projected growth of end-use energy demand were presented (Figure 4). Following this overview, participants engaged in three separate discussions regarding the transportation, buildings, and industrial sectors.

Sector	Fuel	Use (%)
Buildings 21.1 EJ	Electricity	46.6
	Natural Gas	42.1
	Refined Liquids	7.6
	Biomass	3.5
	Other	0.2
Industry 25.8 EJ	Natural Gas	37.3
	Refined Liquids	34.3
	Electricity	13.3
	Coal	6.0
	Renewables	6.0
	Biofuels	2.9
Transportation 28.43EJ	Refined Liquids	96.4
	Natural Gas	3.4
	Electricity	0.1

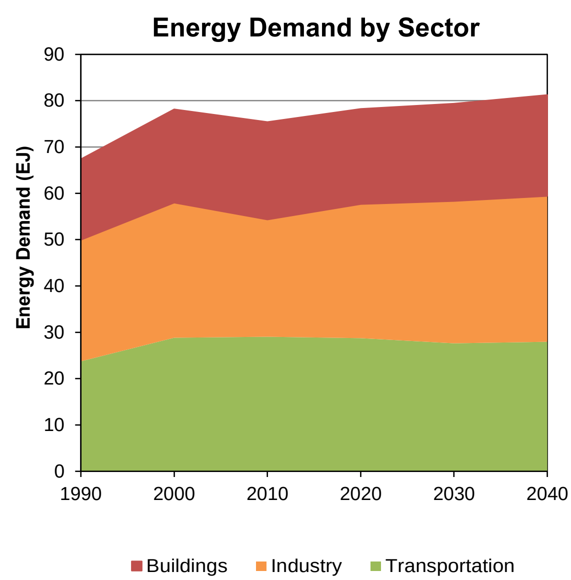


Figure 4. 2013 Delivered Energy Use in the United States (left panel); Historical and Projected Energy Demand by End-Use Sector (right panel).[13,14,15,16]

Transportation

To frame the discussion about energy demand in the transportation sector, workshop participants reviewed scenarios from the literature of potential future energy demand and fuel mixes for light-duty vehicles (LDV) and non-light duty vehicles (NLDV). This presentation included findings from the Transportation Energy Futures Series (Figure 5), and the Quadrennial Technology Review (Figure 6).[17,18]

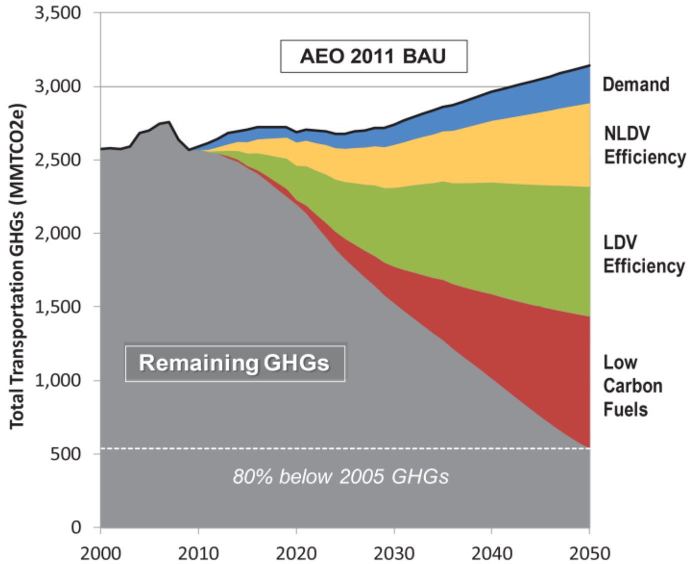


Figure 5. Potential for GHG Reductions in the Transportation Sector. This is a general depiction of how changes in demand, improved efficiency, and use of low-carbon fuels combine to reach an 80% reduction in transportation GHG emissions by 2050. Demand reductions account for approximately 10%; NLDV and LDV efficiency improvements account for approximately 55%; and use of low-carbon fuels account for approximately 35%.[19]

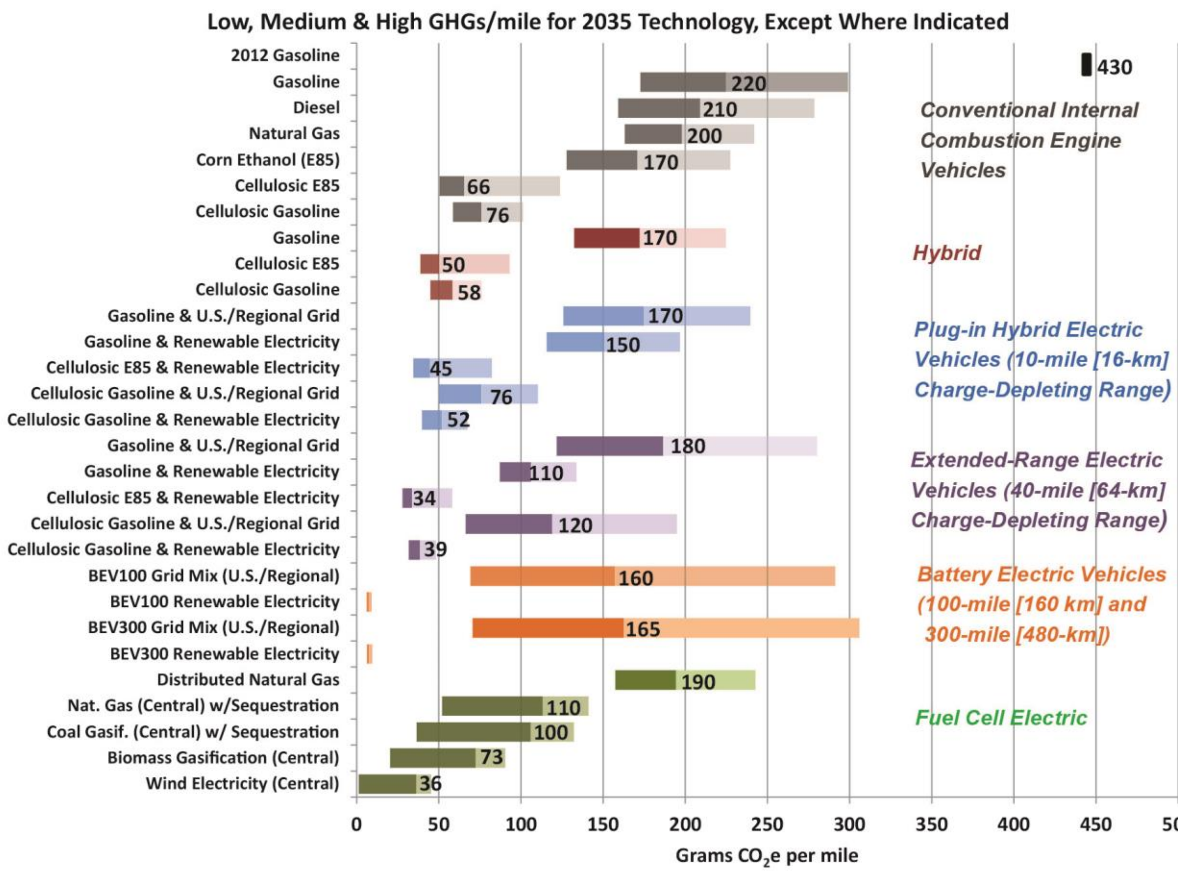


Figure 6. Well-to-Wheels Petroleum Use and GHG Emissions for 2035 Mid-Size Cars. Diverse technology options exist to reduce petroleum use and GHG emissions in the transportation sector. The only options that achieve very high petroleum reductions and very low carbon emissions combine electric drive with low-carbon fuels.[20]

Buildings

To frame the discussion about energy demand in the buildings sector, workshop participants reviewed scenarios from the literature that demonstrate the potential for large-scale electrification of both commercial and residential buildings. In addition, DOE presented research findings that highlight the potential for increased efficiency (decreased energy demand) in commercial and residential buildings (Figures 7, 8, and 9).

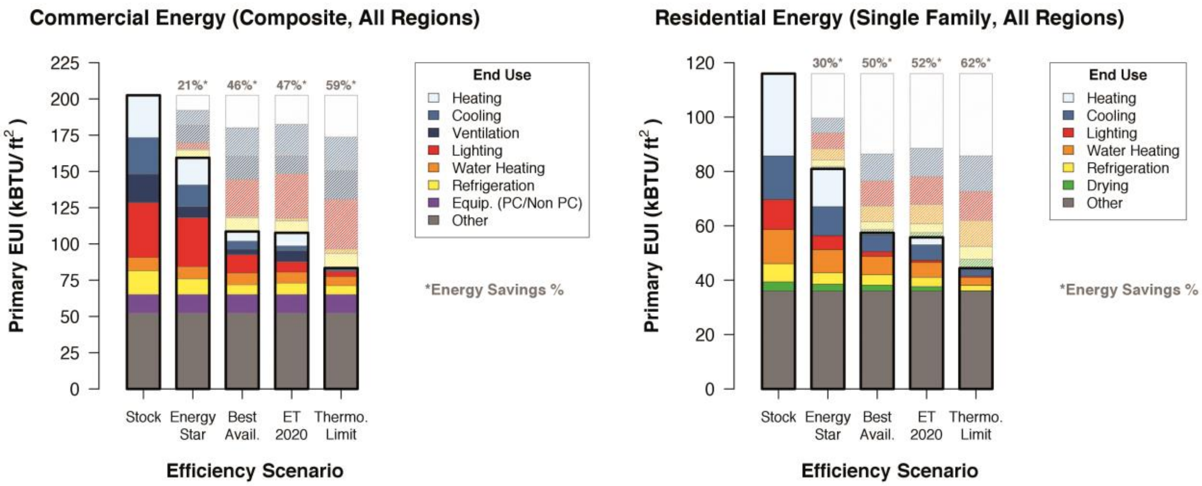


Figure 7. **Primary Energy Use in Residential and Commercial Buildings.** This figure compares primary energy use in commercial buildings(left panel) and residential buildings (right panel) for the current building stock, buildings using ENERGY STAR® equipment, buildings using today's best available technologies, buildings using technologies that meet DOE's emerging technologies (ET 2020) cost and performance goals, and theoretical efficiency limits (e.g., perfect heat pumps). In most cases, the best available technologies have similar performance to those meeting the ET 2020 goals, but planned research advances will make those technologies cost-effective by 2020. Best available, as shown in these figures, does not consider cost. The Other category includes applications such as small electric devices, heating elements, outdoor grills, exterior lights, pool/spa heaters, etc.[21]

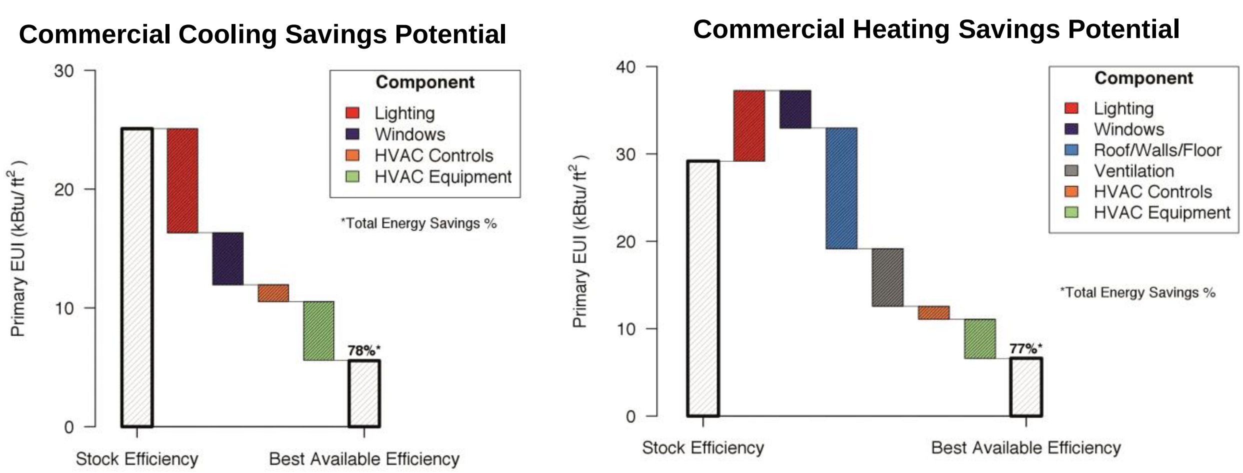


Figure 8. **Commercial Heating and Cooling Savings Potential.** (Left Panel) Improved lighting efficiency decreases the heat energy released into the building by the lighting systems and thus reduces the demand for cooling. Use of the most efficient wall, window, and HVAC equipment that is currently available could reduce the primary energy used in commercial cooling by 78%. (Right Panel) In the heating season, increasing lighting efficiency actually increases the demand for heating energy. This can be offset by improved insulation and heating equipment. Use of the most efficient wall, window, and HVAC equipment that is currently available could reduce primary energy used in commercial heating by 77%.[22]

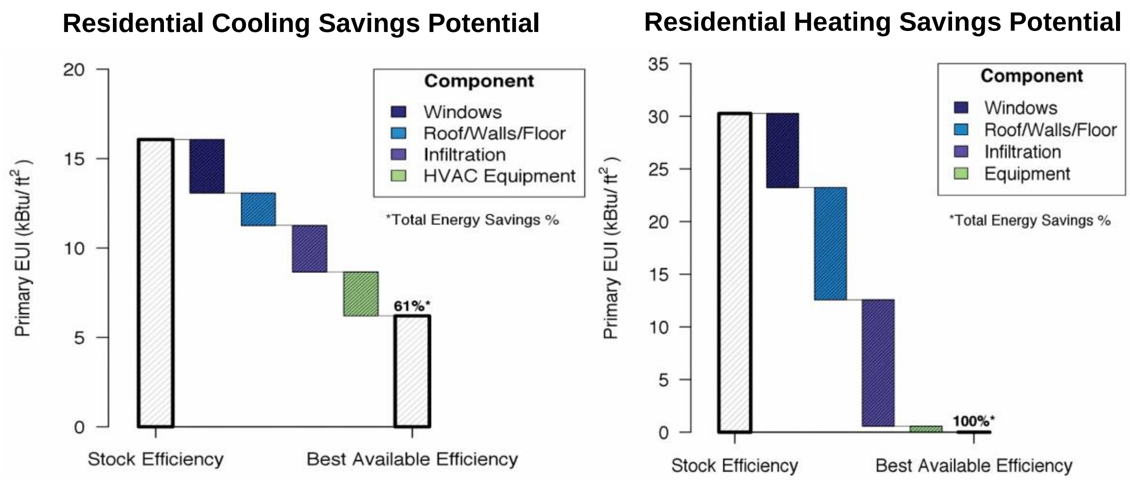


Figure 9. Residential Heating and Cooling Savings Potential. (Left Panel) Use of the most efficient wall, window, and HVAC equipment that is currently available could reduce primary energy use in residential cooling by 61%. (Right Panel) The savings potential of residential heating is even greater since the occupants and household appliances and other devices generate enough heat to meet a large fraction of the home's heating needs. Use of the most efficient wall, window, and HVAC equipment that is currently available could eliminate the primary energy needed for residential heating.[23]

Industry

To frame the discussion about energy demand in the industrial sector, workshop participants reviewed scenarios from the literature that illustrate the potential for efficiency improvements and fuel switching in industrial processes. To further frame the discussion, workshop participants reviewed DOE research that focuses on the potential for reducing energy consumption across diverse, energy-intensive industrial sectors (Figure 10).

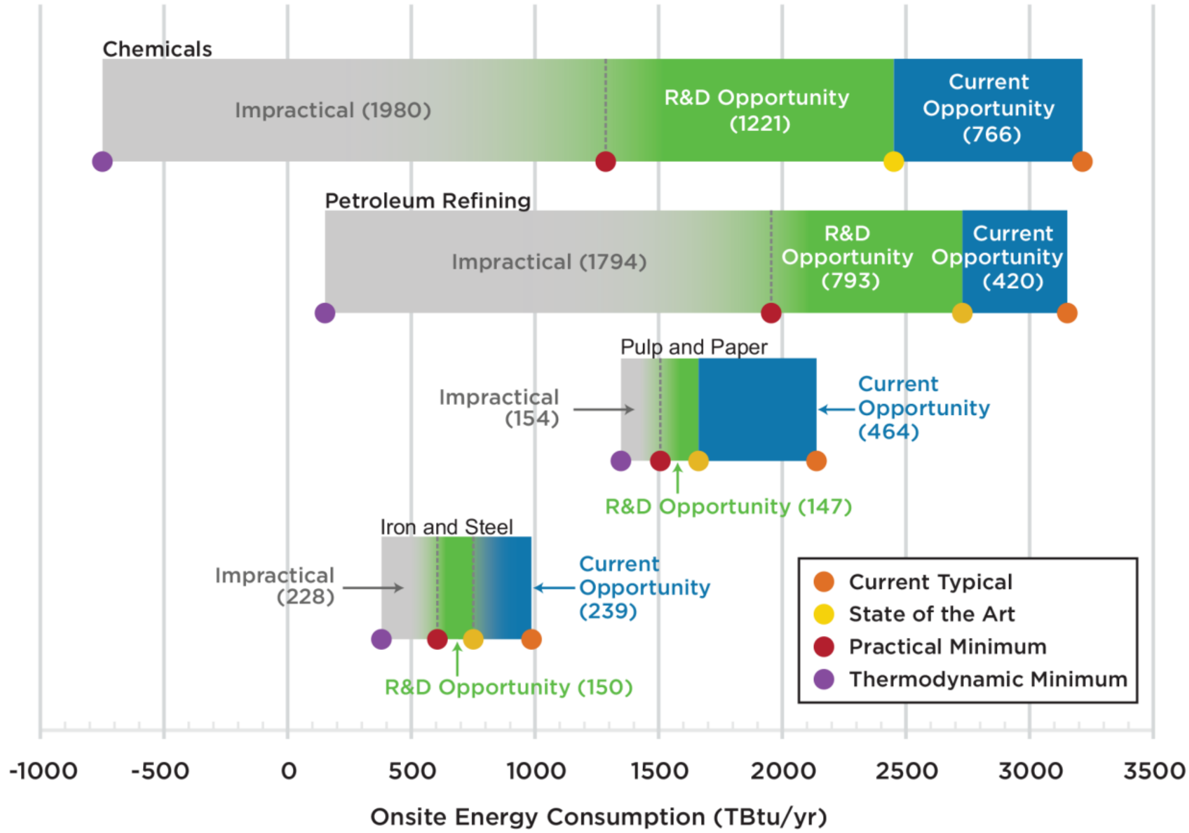


Figure 10. Bandwidth Diagrams Illustrating Energy Savings Opportunities in Four Energy-Intensive U.S. Manufacturing Industries. Current opportunities (blue bands) represent energy savings that could be achieved by deploying the most energy-efficient commercial technologies available worldwide. Future opportunities (green bands) represent savings that could be attained through successful deployment of applied R&D technologies under development worldwide.[24]

IV. KEY THEMES EMERGING FROM THE WORKSHOP

The following section includes a discussion of three key themes that arose during the workshop:

- Reactions of the workshop participants to the framing of the four illustrative pathways, and ways that the pathways might be improved.
- Policy options and strategies associated with 80% economy-wide GHG emissions reductions.
- Technology options and strategies associated with 80% economy-wide GHG emissions reductions.

Participant Reactions to the Illustrative Pathways

In general, participants supported the overall framing of the four illustrative pathways and the use of such pathways as a way to explore the challenges that would be associated with a major transformation of the electric power sector. There was broad support for the construct and plausibility of the Mixed Generation and High Renewable Energy pathways.

A number of questions were raised regarding the High Nuclear and CCS pathway. It was suggested that while there is value in considering these two technologies together as a means to explore mitigation options if wind and solar do not expand substantially beyond today's levels, the issues surrounding CCS and nuclear power are very different. Therefore, multiple workshop participants suggested that it would be worthwhile to consider whether two separate pathways should be constructed around these two technologies. Questions were also raised about the inclusion of bioCCS at large scale in this pathway. One suggestion was to provide an instance of this pathway that minimizes the role of bioCCS.

Participants reacted positively to the presentation of the approximate rates and levels of deployment for low-carbon electricity technologies that would be needed to achieve deep GHG emissions reductions from the electric power sector. Participants indicated that the inclusion of this information and comparison to historical analogs was valuable for understanding the scale of change that would be required over the coming decades to reach 80% economy-wide GHG emissions reductions.

Within the general framing of the illustrative pathways, workshop participants suggested a number of ways that the discussion should be expanded to provide a deeper understanding of the issues associated with the pathways towards 80% economy-wide GHG emissions reductions. The treatment of electricity demand received extensive comment in this regard. Electricity demand was roughly comparable across all of the illustrative pathways produced for this workshop, with the exception of the Mixed Generation with Lower Demand pathway. Yet, at the same time, the scale of electricity demand has enormous implications for low-carbon electricity technology deployment. If demand can be reduced, the same emissions reductions can be achieved with less deployment of new low-carbon electricity technology. It was suggested that a more comprehensive treatment of electricity demand would be valuable in constructing the pathways, including consideration of whether even lower electricity demand pathways would be viable, as well as the possibility for pathways that substantially increase electrification in end uses (e.g., electric cars, heat pumps, and motors for mechanical drive applications) as part of a comprehensive, cross-sectoral strategy.

It was suggested that it would be helpful to provide a more regional perspective on the illustrative pathways. Regional constraints on generation options, regional power system operation characteristics, and differences in regional policy structures could all influence the manner in which these pathways might be implemented. For example, even in a future that most closely resembles the Mixed Generation pathway, some areas of the country might operate in a mode that is closer to the High Renewable Energy pathway, while other regions might rely more heavily on CCS and/or nuclear power. A regional perspective will be important for policy and technology implementation.

Participants suggested that it would be helpful to provide a greater articulation of the potential implications each pathway would have for grid operations and the physical and regulatory structures that surround grid operations. All four illustrative pathways involve historically unprecedented transformations of the electric power sector. Participants repeatedly highlighted a range of issues associated with the operation of such a dramatically different electric power sector, and the need to evolve operational rules, regulations, and technologies in concert with the evolution of the generation mix. Promoting system resiliency and minimizing the chances of failure are important components of any pathway and would need to be understood more effectively in order to design appropriate policies and incentives. These operational considerations include technologies for managing demand response, requirements for reserve capacity, electricity storage technologies, and regulatory structures. It was suggested that a fuller treatment of these operational needs might call for the use of models specifically designed to explore operational needs rather than more aggregate-scale models such as GCAM-USA.

Participants suggested that the discussion of each pathway should be expanded to clearly articulate the technology and policy shifts that would be required to realize each pathway. Additionally, participants indicated that it would be valuable to understand key risks that might emerge in traversing any of the illustrative pathways.

It was suggested that unforeseen technological innovation could arise over the coming decades, which would have a profound influence on the nature of pathways towards 80% economy-wide GHG emissions reductions. A deeper consideration of some of these potential transformational changes was suggested as a way to flesh out the pathways and to ensure that they consider a full range of alternative energy technology futures.

Finally, a number of participants suggested the need for better articulation of the economic characteristics of the pathways. This includes the cost and performance metrics for each of the generation technologies as well as measures such as carbon prices and welfare costs. Participants suggested that it would be easier to determine whether certain pathways would be preferable to others if economic metrics, such as electric power sector costs or electricity prices, were included in the assessment of the pathways.

Participant Comments Regarding Policy Options and Strategies

This section discusses participant comments regarding the design and implementation of energy and climate related policies. The material in this section should not be taken as representing consensus among the participants; the material in this section reflects the topics and issues raised during the workshop that might bear consideration in the construction of a comprehensive energy policy strategy.

- **At the most fundamental level, questions were raised regarding the viability of 80% economy-wide GHG emissions reductions under current policy structures.** Given the rate and scale of deployment required in the illustrative pathways, the observation was made that new or modified policies are needed to encourage the rapid and large-scale deployment of low-carbon energy sources.

- **Participants highlighted that a broad suite of policies will be needed to reach 80% economy-wide GHG emissions reductions.** Policies may include some combination of regulatory structures, economic instruments, sectoral policies, and technology-specific policies (e.g., nuclear relicensing). It was suggested that a carbon price would be helpful tool to achieve emissions reductions. Even if an economy-wide, market-based policy structure is implemented, complementary sectoral-based policies could still be needed. For example, it was suggested that end-use policies would be an important component of any policy portfolio. It was noted that longer-term certainty on policies would help support investments in capital-intensive, low-carbon energy technologies.
- **Participants suggested that it might be possible to achieve 80% economy-wide GHG emissions reductions in the absence of an economy-wide carbon price if other policies were put in place.** Creative policy approaches would be particularly important in the absence of a market-based approach to mitigation. It was also pointed out that a fully sectoral-based approach to mitigation requires careful construction. As an example, policies might be needed to mitigate the impacts of increased electricity prices to ensure that it is feasible to increase electrification in end use sectors.
- **The notion of policy timing was also raised.** One observation was that policies would need to evolve over time as deeper emissions reductions are needed and the energy system continues to transition towards a very different generation mix, increased use of alternative low-carbon fuels in end uses, and potentially greater integration of the demand and supply components of the electric power sector. A related perspective was that policies are needed to drive near-term GHG emissions reductions, given the strategies and technologies that are available but underutilized today.
- **A number of participants highlighted the need for serious consideration of how current policies must evolve to manage and operate an evolving electric power sector with very different operational characteristics than exist today.** Issues that were raised include the treatment of capacity and energy markets, regulatory structures, and policies for enhancing flexibility (e.g., demand response and advanced grid storage). New or modified policy structures would be needed in pathways that include more integration of the demand and supply components of the electric power sector (e.g., through storage in electric cars and greater demand response).
- **Differences in regional policy approaches and circumstances were also raised.** It was suggested that a national policy approach would need to take into account regional variations in electricity generation mixes and electric grid operational modes, as well as state policies and regulations.

- **Participants highlighted the need for policy structures to forestall the creation of new capital that would potentially be subject to early retirement.** Just as deployment of low-carbon sources must increase, the deployment of emitting sources must decrease if the United States is going to achieve 80% economy-wide GHG emissions reductions by 2050. Therefore, a reasonable pathway for the retirement or retrofitting of emitting assets, most importantly coal-fired electricity, needs to be developed. Any new investments in fossil technologies must either be clearly constructed to be able to accommodate CCS, or they will need to be retired prematurely—i.e., before the end of their useful life—if the United States is going to achieve 80% economy-wide GHG emissions reductions. Participants also raised questions about strategies based on installing new gas-fired power plants. Although gas-fired electricity generation might reduce emissions in the near-term, many of these power plants would need to be retired or retrofitted with CCS in the long run to achieve 80% economy-wide GHG emissions reductions.

Participant Comments Regarding Technology Strategies

This section discusses participant comments that have implications for energy technology strategies. The material in this section should not be taken as representing consensus among the participants; the material in this section reflects the topics and issues raised during the workshop that might bear consideration in the construction of a comprehensive technology strategy.

- **Participants suggested the need for a comprehensive technology strategy that fully integrates demand- and supply-side goals.** As noted in the discussion of the four illustrative pathways, reductions in electricity demand can reduce the magnitude of low-carbon electricity technology deployments that are needed for 80% economy-wide GHG emissions reductions. However, participants also noted that substantial electrification of the transportation, buildings and industrial sectors may be a key element of future low carbon pathways. In addition, electricity supply and demand may need to be more integrated in the context of future electricity mixes with different proportions of variable and baseload power sources than exist today. For example, the notion was raised of integrating the electricity storage capability of electric vehicles into the grid.
- **A wide range of opinions was provided regarding the potential for energy demand reductions in end-use sectors.** Some participants suggested major reductions in energy use are possible, while others suggested that these options are less accessible.
- **As noted above, it was suggested that technology innovation over the coming decades could have a profound influence on the nature of pathways to 80% economy-wide GHG emissions reductions.** This includes unexpected technologies as well as technologies that have been extensively explored but are currently perceived as challenging or untested in large-scale commercial application. Understanding these potential transformative technologies would be important for a comprehensive energy technology strategy.
- **The notion of operational concerns associated with very different electricity mixes led to a discussion of technologies that could enhance grid flexibility.** It was pointed out that electric power systems with high variable load would benefit from quick ramping capabilities, storage, and a flexible demand side. It was suggested that advanced electricity storage technologies could be important enablers of a dramatic transformation of the electric power sector.

- **It was noted that improvements in the cost and efficiency of GHG emissions mitigation technologies in general will make it societally, politically, and economically easier to achieve the major energy system transformation that is needed to achieve 80% economy-wide GHG emissions reductions.** Within this context, it was suggested that there is a need for a better understanding of the ways in which deployment policies can drive technological innovation and how they interact with R&D investments. Another issue that was raised was the notion that a comprehensive domestic strategy for GHG emissions mitigation must take into account synergies with international R&D and deployment efforts. It was suggested that we are already seeing the effects of technological advances from China and India in the United States.

V. CONCLUSIONS

The workshop upon which this report is based was intended to help EPSA achieve the following goals:

- Gather input to support the development of a set of representative pathways towards an 80% economy-wide reduction in GHG emissions by 2050, with a particular focus on electric power sector pathways; and
- Identify the key characteristics, challenges, and requirements of the different pathways.

Workshop participants generally supported the composition of the four illustrative pathways, with a number of suggestions regarding the treatment of CCS, nuclear power, and electricity demand. Based on the discussions at the workshop, a number of key themes emerged regarding policy and technology needs for meeting 80% economy-wide GHG emissions reductions.

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[23] DOE, *Quadrennial Technology Review*, 155.
[24] DOE, *Quadrennial Technology Review*, 196.

LIST OF WORKSHOP PARTICIPANTS

Name	Organization
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WORKSHOP AGENDA

9:00 a.m.	–	9:30 a.m.	Welcome, Building Orientation, and Roundtable Introductions
9:30 a.m.	–	10:00 a.m.	**Session 1:** Overview of 80% Reduction Goal and Scope of Needed Reductions
10:00 a.m.	–	12:30 p.m.	**Session 2:** Electricity Supply
12:30 p.m.	–	12:45 p.m.	Break
12:45 p.m.	–	1:45 p.m.	Working Lunch **Session 2 Continued:** Electricity Supply
1:45 p.m.	–	4:30 p.m.	**Session 3:** Energy Demand
4:30 p.m.	–	5:00 p.m.	Conclusions and Next Steps