III Building a Clean Electricity Future

This chapter explores the essential elements of a clean electricity system, and identifies the policy, market, and technology innovations needed to improve its environmental performance. The United States has made substantial progress in reducing the environmental impact of the electricity system, but much work remains. The chapter first explores the GHG emissions from the power sector and the availability of low- and zero-carbon electricity sources, including nuclear, natural gas, solar, wind, hydropower, biomass, and geothermal sources. The next sections detail the interaction between clean electricity systems and key options and features, such as energy efficiency, demand response, flexibility, and storage. The chapter includes a discussion of how the interplay of technology, markets, and policy can lead to a cleaner electric system, and how a cleaner electric system can support economy-wide decarbonization through the further electrification of other end-use sectors.

Key Findings for Building a Clean Electricity Future

- A clean electricity system reduces air and water pollution, lowers GHG emissions, minimizes waste, and limits the impact to the ecosystem in areas such as water and land use.
- Deep decarbonization of the electricity system is essential for meeting climate goals; this has multiple economic benefits beyond those of environmental responsibility.
- The United States is the largest producer and consumer of environmental technologies. In 2015, the U.S. environmental technology and services industry employed 1.6 million people, had revenues of $320 billion, and exported $51 billion worth of goods and services.
- Though the U.S. population and economy have grown, between 1970 and 2014, aggregate emissions of common air pollutants from the electric power sector dropped 74 percent, even as electricity generation grew by 167 percent.
- U.S. carbon dioxide (CO_2) emissions from the power sector have substantially declined. Between 2006 and 2014, 61 percent of the reductions in CO_2 intensity were attributed to switching from coal- to gas-fired power generation, and 39 percent were attributed to increases in zero-emissions generation.
- The increasing penetration of zero-carbon variable energy resources (VERs) and deployment of clean distributed energy resources (DERs) (including energy efficiency) are critical components of a U.S. decarbonization strategy.
- It is beneficial to a clean electricity system to have many options available, as many of the characteristics of clean electricity technologies complement each other.
- Currently, 29 states and Washington, D.C., have a Renewable Portfolio Standard (RPS), and 23 states have active and binding Energy Efficiency Resource Standards (EERSs) for electricity. States that have actively created and implemented such electricity resource standards and other supporting regulatory policies have seen the greatest growth in renewables and efficiency.
- The integration of variable renewables increases the need for system flexibility as the grid transitions from controllable generation and variable load to more variable generation and the need and potential for controllable load. There are a number of flexibility options such as demand response (DR), fast ramping natural gas generation, and storage.
- Energy efficiency is a cost-effective component of a clean electricity sector. The average levelized cost of saved electricity from energy efficiency programs in the United States is estimated at $46 per megawatt-hour (MWh), versus the levelized cost of electricity (LCOE) for natural gas combined-cycle (NGCC) generation, with its sensitivity to fuel prices, at $52 to $78/MWh.[1]
- Electricity will likely play a significant role in the decarbonization of other sectors of the U.S. economy as electrification of transportation, heating, cooling, and industrial applications continues. In the context of the Quadrennial Energy Review (QER), electrification includes both direct use of electricity in end use applications as well as indirect use whereby electricity is used to make intermediate fuels such as hydrogen.
- Realizing greenhouse gas (GHG) emissions reductions and other environmental improvements from the electricity system to achieve national goals will require additional policies combined with accelerating technology innovation.
- Improving understanding of the electricity system and its dynamics through enhancements in data, modeling, and analysis is needed to provide information to help meet clean objectives most cost-effectively.
- Decades of Federal, state, and industry innovation investments have significantly contributed to recent cost reductions in renewable energy and energy efficiency technologies.

- Innovation in generation, distribution, efficiency, and demand response technologies is essential to a low-carbon future. Innovation combined with supportive policies can provide the signal needed to accelerate deployment of clean energy technologies, providing a policy pull to complement technology push.
- Nuclear power currently provides 60 percent of U.S. zero-carbon electricity, but existing nuclear merchant plants are having difficulty competing in restructured electricity markets due to low natural gas prices and flat or declining electricity demand. Since 2013, six nuclear power reactors have shut down earlier than their licensed lifetime, and eleven[a] others have announced plans to close in the next decade. In 2016, two states, Illinois and New York, put policies in place to incentivize the continued operation of existing nuclear plants.
- Enhanced oil recovery (EOR) operations in the United States are commercially demonstrated geologic storage, and could provide a market pull for the deployment of carbon capture, utilization, and storage (CCUS).
- Federal laws currently limit the ability of regulated utilities to utilize Federal tax credits in the same manner as private and unregulated developers. Publicly owned clean energy projects cannot benefit from the clean energy tax credits because tax equity investors cannot partner directly with tax-exempt entities to monetize tax credits.
- Low-income and minority communities are disproportionately exposed to air quality and water quality issues associated with electric power generation. Compared to the U.S. population overall, there is a greater concentration of minorities living within a three-mile radius of coal- and oil-fired power plants. In these same areas, the percentage of the population below the poverty line is also higher than the national average.
- Some energy technologies that reduce GHG emissions, such as carbon capture, utilization, and storage (CCUS), concentrated solar power (CSP), and geothermal generation, have the potential to increase energy's water intensity; others, such as wind and photovoltaic (PV) solar power, can lower it. Dry cooling can reduce water intensity but may increase overall GHG emissions by decreasing generation efficiency. Though there can be a strong link between energy and water efficiency in energy technologies, many research, development, demonstration, and deployment (RDD&D) funding criteria do not incorporate water use or water performance metrics. Designing technologies and optimizing operations for improved water performance can have both energy and water benefits.
- There is currently no centralized permanent-disposal facility for used nuclear fuel in the United States, so this radioactive material is stored at reactor sites in 35 states awaiting development of consolidated storage facilities and/or geologic repositories.
- Coal combustion residuals (CCRs), such as coal ash and scrubber slurry, are the second most abundant waste materials in the United States, after household waste.
- There is a range of decommissioning needs for different types of power generation facilities.

3.1 Building a Clean Electricity Future

A recent poll noted that "73% of voters support a national energy policy that ensures a secure supply of abundant, affordable, and available energy for the American people in an environmentally responsible manner."[2] The views of the respondents in this poll suggest that the American people do not view environmental and other goals to be in conflict; the United States has consistently been able to manage environmental pollution while also maintaining electric reliability, growing the economy, and supporting millions of jobs.

[a] Note that six of these reactors (the New York and Illinois reactors) are expected to remain open with the passage of Clean Energy Standards (CESs) in those states.

While electricity is the workhorse of our modern economy, it is also responsible for more than 30 percent of U.S. greenhouse gas (GHG) emissions.[3] Reducing GHG emissions is a key imperative for the power sector. When considering the scale of this challenge, it is important to recognize that the reduction of adverse public health and environmental impacts from electricity generation has been one of the major U.S. environmental success stories of the 20th century. Since 1970, emissions of common air pollutants from the electric power sector have decreased by more than half.[4] In the near term, carbon dioxide (CO_2) emissions from the energy sector fell by 10 percent from 2008 to 2015, while the economy grew by more than 10 percent over this same period.[5] This success is even more notable because it occurred in conjunction with increased electricity generation and significant, sustained economic growth.

Enabling a clean, flexible, reliable electricity system will require continuous cost reductions and improved environmental performance of energy technologies. There are multiple avenues for improving the environmental performance of the electricity system by building on past successes. A cleaner electricity generation system can be achieved through a combination of technological innovation and incentives, national environmental policy, innovative state policy, and financial mechanisms. These findings are supported by detailed modeling of scenarios for the electricity system, which demonstrates the role of innovation and effective policy in improving environmental outcomes. The chapter also examines approaches to further reducing the environmental impacts of electricity on air and water, as well as mitigating relevant land use challenges and environmental justice issues affecting local communities.

There are, however, ongoing environmental impacts associated with electricity systems that merit sustained policy and regulatory focus and support. These include climate change; water use for power generation; land use impacts of power generation, transmission, and distribution; environmental justice issues associated with electricity; and decommissioning of generation assets. Today, the United States has an opportunity to build on its substantial experience of joint environmental and economic success to address the central challenge of climate change mitigation, along with environmental challenges associated with electricity generation, distribution, transmission, and consumption.

3.2 CO_2 Emissions and the Electricity System

The growth in U.S. electricity consumption has gradually slowed from 9.8 percent per year in the 1950s to 0.5 percent per year over the past decade, due in part to "slowing population growth, market saturation of major electricity-using appliances, efficiency improvements in appliances, and a shift in the economy toward a larger share of consumption in less energy-intensive industries."[6, 7] In 2014, electricity accounted for 39 percent of total primary energy consumption.[b] The residential and commercial sectors each consumed about the same share of total electricity—37 percent and 36 percent, respectively—with the industrial sector accounting for 26 percent of electricity demand. Electricity use in the transportation sector was minimal, constituting less than 1 percent of total U.S. electricity consumption.[8] Electricity use is projected to grow slowly, and its share of total delivered U.S. energy consumption is expected to increase only slightly by 2040.[c, d, 9]

Electric power generation is one of the largest sources of CO_2 emissions in the United States.[10] Over 99 percent of the GHG emissions attributed to the power sector are the result of the combustion of fossil

[b] 38.4 quads were used to generate 3,900 terawatthours (TWh) of electricity. Total energy consumption in 2014 was 98.3 quads.
[c] According to the EPSA Base Case, which incorporates all existing U.S. policies but assumes no new policies, electricity use is projected to grow at an annual rate of 0.65 percent between 2014 and 2040. In terms of delivered energy, the electricity sector's share is projected to increase from 18 percent in 2014 to 19 percent in 2040, and overall electricity demand is projected to increase from 12.76 to approximately 15 quadrillion British thermal units (quads).
[d] In terms of total primary (or source) energy, the electric sector's share is projected to increase from 13 percent in 2014 to 14 percent in 2040, according to the EPSA Base Case, which incorporates all existing U.S. policies but assumes no new policies.

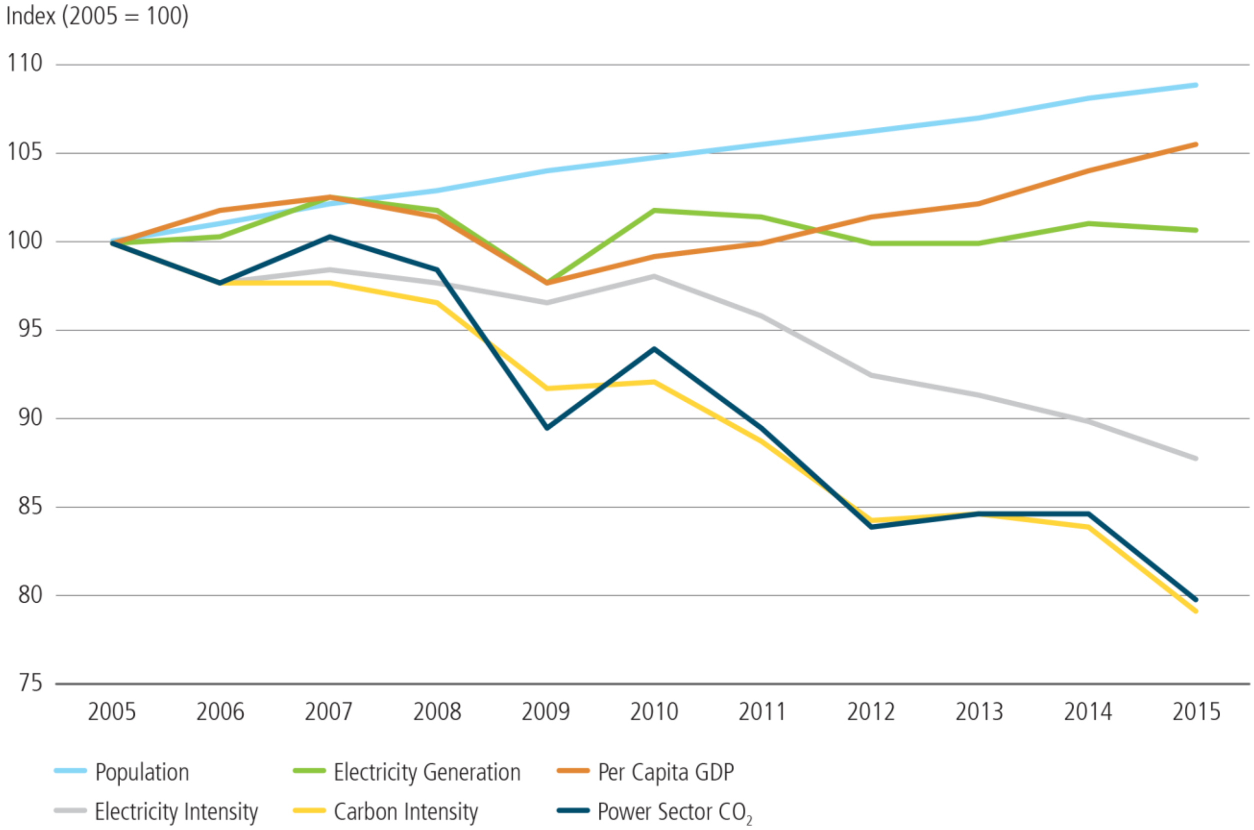
fuels for power generation. In 2014, CO_2 from coal combustion accounted for over three-quarters of U.S. power-sector GHG emissions, while CO_2 from the combustion of natural gas contributed approximately 21 percent of U.S. power-sector GHG emissions.[11, 12] The emission *rate*—the amount of CO_2 emitted per unit of electricity generated—is a key indicator of the climate impact of electricity generation, and varies significantly by fuel and technology. The current, average emission rate of NGCC plants in the United States is 60 percent less than that of average coal-fired plants.[13,14] Nuclear power and renewable electricity generation have no direct emissions associated with electricity generation.

Electric power generation provides service to end-use economic sectors. When attributing current U.S. power-sector GHG emissions to end-use economic sectors, the industrial sector is responsible for approximately 26 percent of electricity-related emissions, and the remainder is split evenly between the residential and commercial sectors, at 36 percent and 35 percent, respectively.[e, 15] This sectoral attribution highlights a dual pathway for reducing total carbon emissions: (1) decarbonization of the electricity sector itself, and (2) electricity efficiency improvements within the end-use economic sectors.

3.2.1 Decarbonization of the Electricity System

After a gradual decline from 1970 to 2005, the CO_2 emission rate (kilograms of CO_2/MWh) of electricity generation fell to 20.9 percent below 2005 levels in 2015.[16]

Figure 3-1. Trendlines in Emissions Drivers, 2005–2015[17, 18, 19]



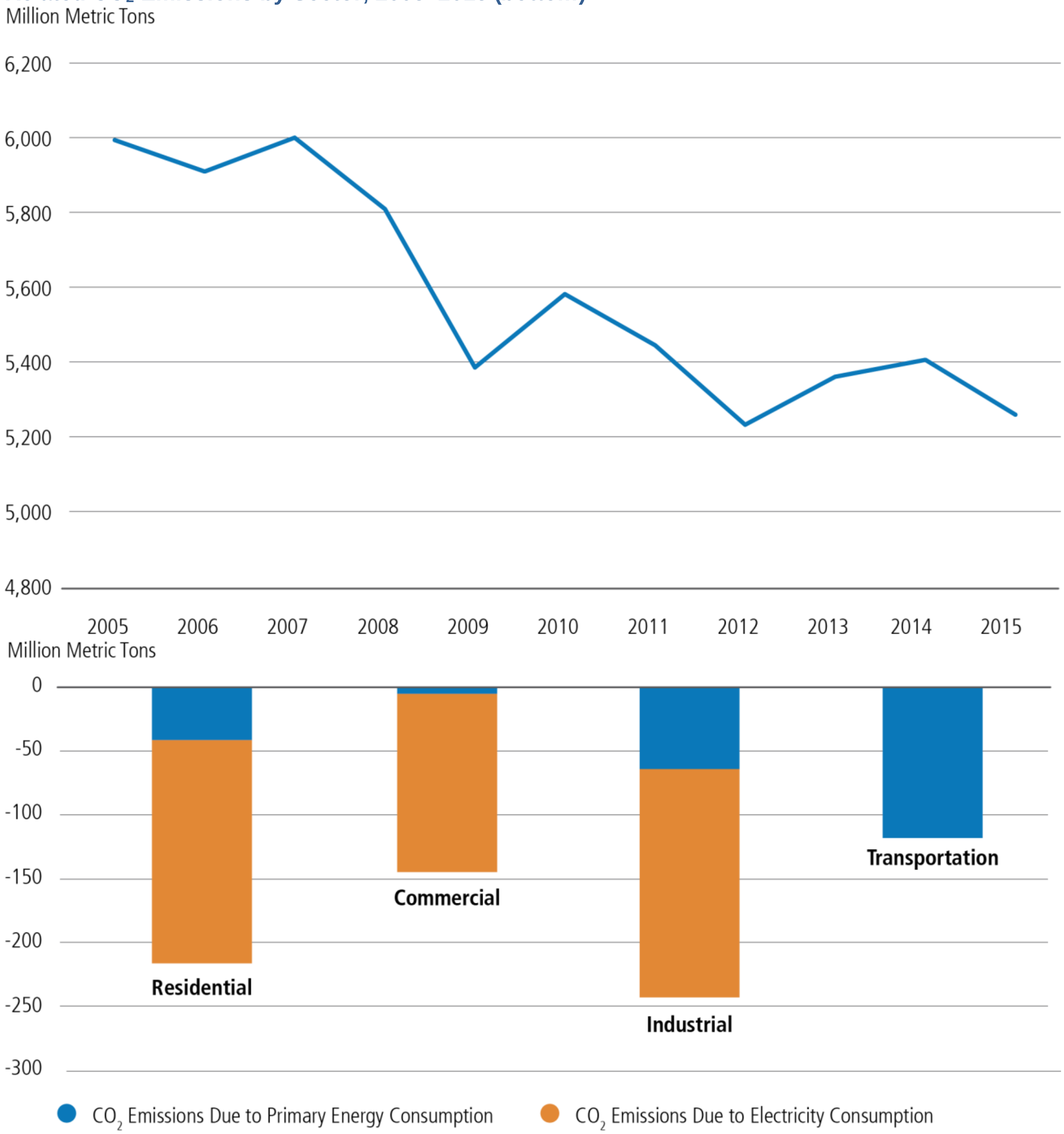
The population growth, per capita gross domestic product (GDP), and electricity intensity of the economy all factor into total U.S. electricity demand. While growth in population and per capita GDP has placed

[e] The remaining electricity-related emissions are from other sectors that account for minor amounts of electricity-related emissions in the United States, including agriculture (3 percent) and transportation (0.2 percent).

upward pressure on power-sector demand, this growth has been partially offset by a decline in the electricity intensity of the economy.

Slow growth in per capita electricity consumption, greater electricity productivity (measured in dollars of gross domestic product [GDP] per kilowatt-hour [kWh] of electricity), and a decline in the CO_2 emission rate from electricity generation have already helped decouple economic growth from electricity consumption (and, consequently, electricity generation–related CO_2 emissions).[20] U.S. power-sector CO_2 emissions have declined even while the population and the economy have grown. As shown in Figure 3-1, between 2005 and 2015, the U.S. GDP grew by 14.8 percent, and the amount of electricity consumed per dollar of GDP declined by 12 percent due to greater economic productivity per kWh of electricity consumed. As shown in Figure 3-2, energy-related CO_2 emissions reductions in recent history have occurred in the electric power sector largely because of the decreased use of coal and the increased use of natural gas for electricity generation.

Figure 3-2. U.S. Energy-Related CO_2 Emissions, 2005–2015 (*top*), and Change in U.S. Energy-Related CO_2 Emissions by Sector, 2005–2015 (*bottom*) [21, 22]



After increasing in 2013 and in 2014, energy-related CO_2 emissions fell in 2015. In 2015, U.S. energy-related CO_2 emissions were 12 percent below the 2005 levels, mostly because of changes in the electric power sector.

In addition to these market and technology trends, a wide array of policies and measures developed and implemented at the Federal, state, and local levels have helped to mitigate GHG emissions from the U.S. power sector. These include performance-based regulations and standards, economic instruments, information programs, and diffusion of key technologies from robust RD&D investments. Many policy approaches cross these categories. Federal and state emissions trading programs, for example, combine performance-based regulation with trading of marketable credits or allowances, the latter of which are economic instruments.

Upgrading and investing in the transmission system is one critical measure that could have far-reaching impacts for the environment, could increase system flexibility and resilience, and save electricity consumers as much as $47 billion annually.[23] A modernized and expanded transmission system has the potential to interconnect clean generation (for both short distances as well as connecting remote clean generation sources to population centers) while also enhancing a national electricity market in which all energy assets can fairly compete. State clean electricity goals are also facilitated through transmission upgrades, an example being the New York Independent System Operator (ISO), which is looking to make more effective use of rurally located wind and hydropower resources by connecting them with high electricity-demand centers like New York City.[24]

It can be challenging to evaluate whether transmission policies and regulations are simultaneously achieving their intended reliability benefits in the face of unprecedented physical change, and are providing adequate capacity to cost-effectively address environmental requirements. Such evaluation requires new analyses, but for those analyses to be valid, data with greater scope, frequency, and resolution must be made available. Expanded transmission data resources will facilitate the development of effective Federal and state policies and regulations that will affect reliability and environmental goals, give those that invest in the transmission system insights into potential business opportunities, and provide a broad range of stakeholders with a greater understanding of the fairness of operations in providing non-discriminatory access. The Federal Energy Regulatory Commission (FERC) has recognized the importance of electricity transmission in a clean future and worked to expedite the contribution of transmission through FERC Order Nos. 890 and 1000. Order No. 890 (2007) required that transmission planning be open to stakeholders. Order No. 1000 (2011) added interregional coordination, competition among transmission owners, and cost allocation reform. Order No. 1000 also enables transmission projects that support public policy goals, such as moving renewable energy from distant sources to load centers, to be facilities with income that is subject to FERC regulatory authority.

Equitable cost allocation among customer beneficiaries, especially for larger and interregional transmission investments, is a significant challenge in the implementation of the FERC Order No. 1000 regional planning process. Differing regional approaches to meeting FERC Order No. 1000 principles for cost allocation—particularly the definition of "beneficiary"—have made the implementation of Order No. 1000 complex. The implementation of FERC Order No. 1000 regional cost allocation principles is relatively new, so it is hard to assess the effectiveness of the process to date in achieving public policy goals. Going forward, more systematic monitoring of activities and systematic data collection will be needed to assess whether Order Nos. 890 and 1000 are achieving their goals.

3.2.2 Low and Zero-Carbon Power Generation

A consistent theme from a vast body of climate science research suggests that deeper decarbonization is necessary to reduce emissions sufficiently to minimize the most serious impacts of climate change.[25] This will require, in part, an enhanced portfolio of lower- and zero-carbon generation technologies, such as renewables, nuclear power, and fossil generation with carbon capture, utilization and storage (CCUS).

The national and regional generation mix has changed over the past few decades (Table 0-1), and additional changes are projected for 2040. In 2005, the top six generation sources in descending order were coal, nuclear, gas, hydro, petroleum, and non-hydro renewables. Natural gas and non-hydro renewables, especially wind and solar, have become much more prominent in the fuel mix, largely due to low-cost, abundant natural gas supplies, lower cost wind and solar generation technologies, and a range of federal and state policies that provide incentives for a range of clean generation technologies. Comparing the costs of different electric generating technologies is challenging, particularly as the costs of many technologies and fuels vary due to the interplay of innovation, policy, markets, and future uncertainty. One common approach is to compare technologies using the LCOE.[26] There are limitations of using LCOE, particularly for capital-intensive technologies, as this metric is sensitive to assumptions about the cost of capital, among other factors.[f]

Table 0-1. Change in Generation from Major Fuel Type, 2009–2014[27]

	Coal		Natural Gas		Nuclear		Non-Hydro Renewable		Total	
	Absolute Change (TWh)	Percent Change	Absolute Change (TWh)	Percent Change	Absolute Change (TWh)	Percent Change	Absolute Change (TWh)	Percent Change	Absolute Change (TWh)	Percent Change
U.S.	-171.3	-10	204.6	22	-1.7	0	130.8	85	132.0	3
WECC	-13.8	-6	-4.3	-2	-10.3	-15	43.4	92	11.9	2
SERC	-53.9	-11	94.8	51	3.8	1	12.7	52	49.8	5
RFC	-83.0	-15	65.1	85	12.1	5	17.5	102	13.5	1
NPCC	-17.4	-62	11.8	12	0.2	0	14.5	148	-6.4	-2
SPP	-0.8	-1	-5.7	-10	-0.2	-2	4.0	29	3.4	2
MRO	-9.6	-6	2.7	31	-3.9	-11	19.2	105	12.2	6
FRCC	-4.1	-7	30.6	29	-1.2	-4	0.0	-1	9.7	4
TRE	11.4	10	9.7	6	-2.2	-5	19.4	105	37.8	12
Alaska	-0.1	-11	-0.3	-8	0.0	0	0.2	1,484	-0.7	-10
Hawaii	0.0	1	0.0	0	0.0	0	0.5	74	-1.3	-12

In recent years, the electricity generation mix in the western United States has shifted from fossil fuels and nuclear power to non-hydro renewables. In the eastern part of the United States, generation has shifted primarily from coal to natural gas. Texas has seen a growth in generation from both coal and non-hydro renewables. Acronyms: terawatt-hours (TWh), Western Electricity Coordinating Council (WECC), SERC Reliability Corporation (SERC), Reliability First Corporation (RFC), Northeast Power Coordinating Council (NPCC), Southwest Power Pool (SPP), Midwest Reliability Organization (MRO), Florida Reliability Coordinating Council (FRCC), Texas Reliability Entity (TRE).

In the past 10 years, the share of electricity generation from low- and zero-carbon-emitting energy technologies has been growing. Zero-emitting sources account for 33.4 percent of power-sector generation. In 2015, nuclear power accounted for about 20 percent of power-sector electricity, followed by conventional hydropower at 6 percent, and other renewable forms of generation combined—including wind, solar, geothermal, and biomass—at around 7 percent.[28] However, generation from nuclear and hydropower has been relatively flat. Most of the growth in electricity generation from zero-emitting energy technologies since 2005 is from renewable sources, such as wind and solar power.[29] CCUS is a potentially significant technology option to enable very-low-carbon generation from fossil fuels and biomass.

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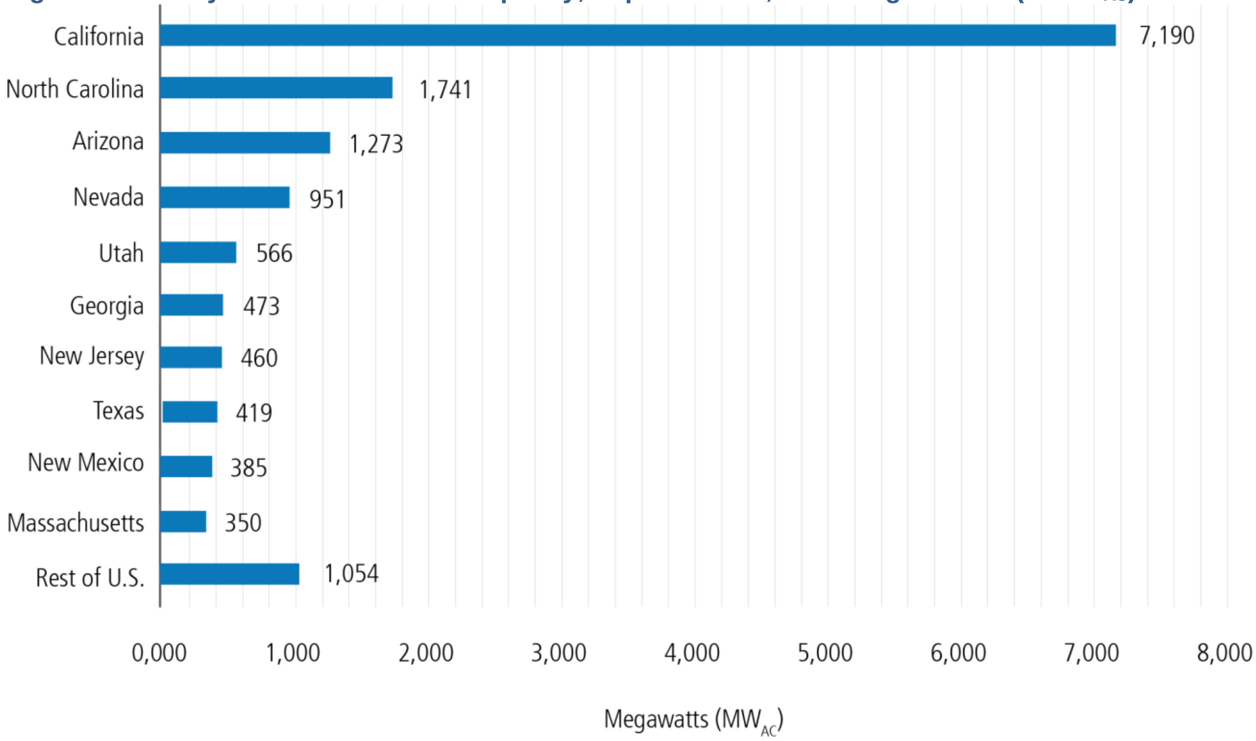
[f] For a discussion of the limitations of LCOE, see Energy Information Administration (EIA), *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016* (Washington, DC: EIA, 2016), 1, http://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

3.2.2.1 Wind and Solar: Zero-Carbon Variable Energy Resources

Cumulative wind capacity has grown from 25 gigawatts (GW) in 2008 to 74.4 GW in 2015.[30] In 2015, wind accounted for 41 percent of new electric generation capacity in the United States and provided 4.7 percent of total electricity generation.[31, 32, 33] Similarly, utility-scale solar generation capacity has grown from less than 0.1 GW in 2008 to 11.9 GW in 2015, a factor of over 168.[34] There are now over 1 million installed PV systems across the United States.[35, 36] EIA estimates that total U.S. solar net generation (PV and thermal) was 4.7 million megawatthours in October 2016, with 33.94% of that total coming from distributed solar PV.[37]

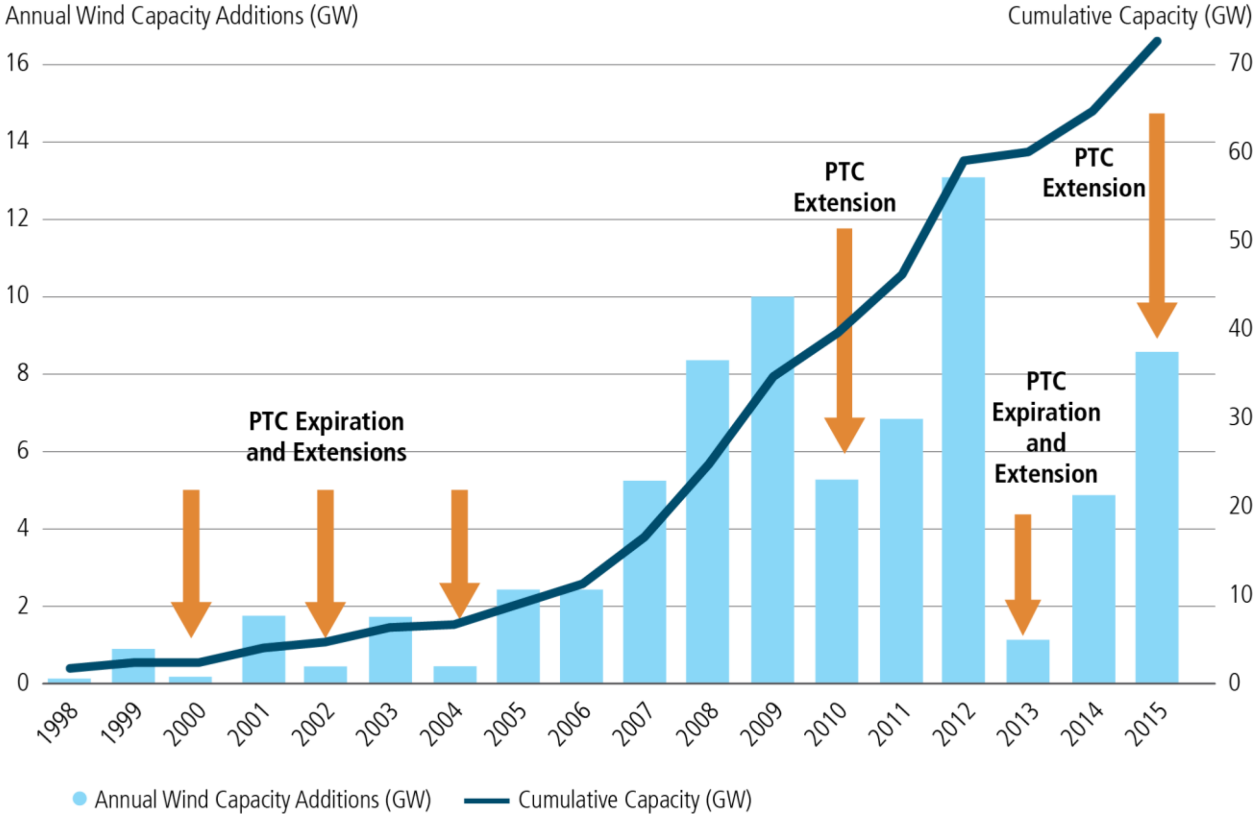
Figure 3-3. Utility-Scale PV Installed Capacity, Top 10 States, as of August 2016 (in MW_{AC})[38]



Utility-scale PV installed capacity is distributed unevenly across the United States. California comprises almost half of the installed utility-scale PV capacity in the country, followed by North Carolina, and the Southwest of the United States with Arizona, Nevada, and Utah. MW_{AC} denotes alternating-current megawatts.

The price of installed residential- and utility-scale solar PV is projected to fall below $2 per W_{DC} (direct current wattage) and $1.15/$W_{DC}$, respectively, in the next 10 years. Solar PV electricity generation is projected to grow by a factor of 17 from 2015 to 2040 and reach an installed capacity of over 100 GW.[39] The Department of Energy's (DOE's) SunShot program has a goal of achieving an LCOE of 6 cents/kWh) for utility-scale PV in 2020 and 3 cents/kWh by 2030.[40] Despite the rapid growth of distributed- and utility-scale PV, these resources contribute generation equivalent to about 0.4 percent and 0.6 percent of U.S. demand, respectively.[41, 42] In the United States, California dominates solar PV with about 50 percent of the Nation's installed capacity (Figure 3-3), due in large part to legacy statewide incentive programs, such as the California Solar Initiative, as well as the state's high retail electricity rates and solar resource potential.

Figure 3-4. Relationship between the Production Tax Credit (PTC) and Annual Wind Capacity Additions[43]



The Production Tax Credit (PTC) has accelerated wind project deployment significantly—between 2000 and 2013, cumulative wind capacity grew from under 5 GW to over 60 GW—though capacity additions noticeably track the PTC expiration and extension schedule.

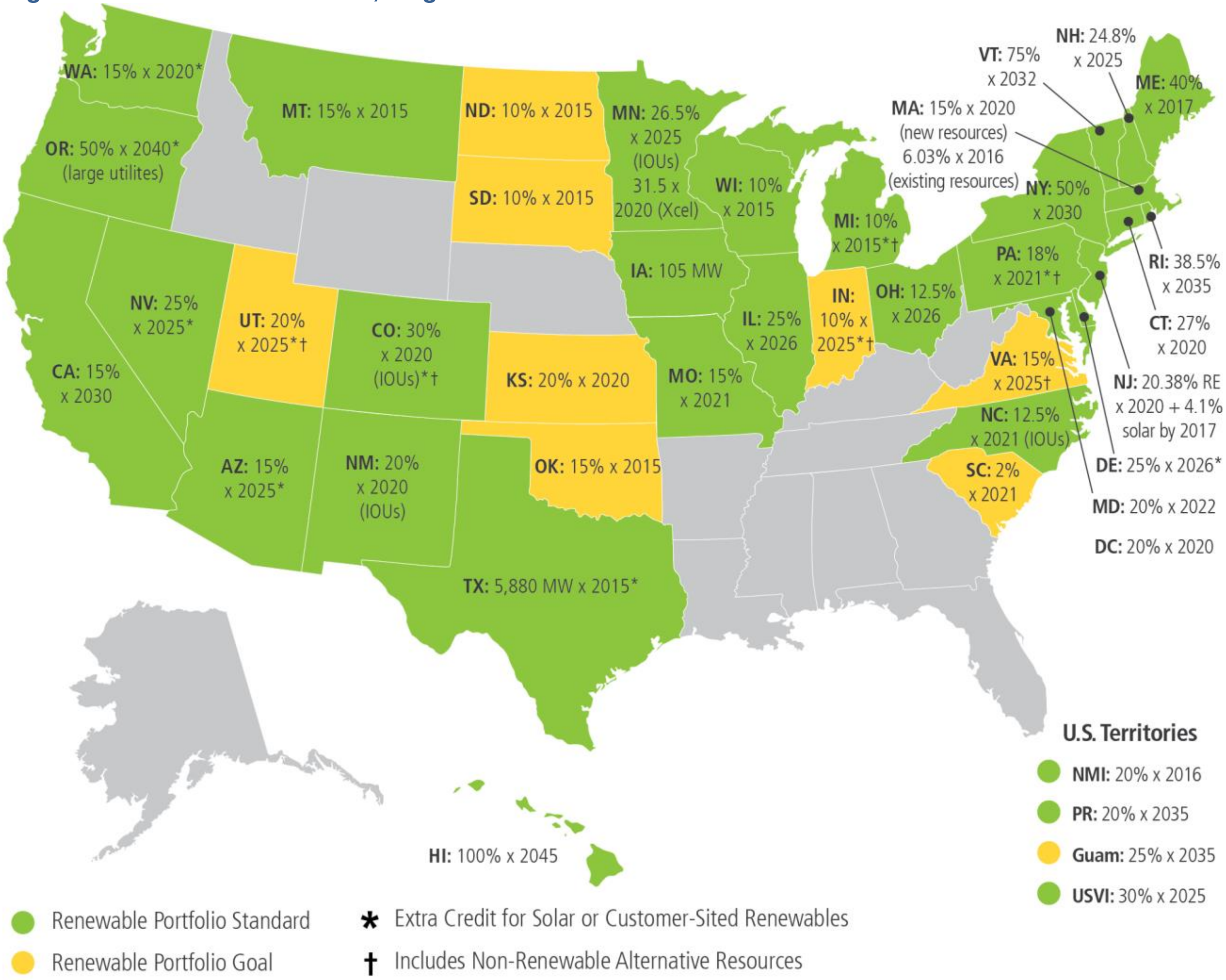
Technology improvements in wind turbines—including taller turbines, longer blades, and advanced turbine designs—have enabled substantial cost reductions for wind power. Power purchase agreements for wind have fallen from rates as high as 7 cents/kWh in 2009 to around 2 cents/kWh inclusive of the Production Tax Credit (PTC) in 2015, driven by wind deployment in excellent resource locations in the interior regions of the country.[44] It is also projected that these technology improvements will enable an expansion of the geographic distribution of wind power's technical potential to new regions of the United States.[45]

Declining costs for wind and solar have been spurred by industry innovation as well as a variety of Federal and state policies that accelerate deployment. Major policies include the renewable energy tax credits at the Federal level and the RPSs at the state level. At the Federal level, the Investment Tax Credit (ITC) and PTC established under the Energy Policy Act of 1992 are two key Federal tax incentives that have been instrumental in accelerating the construction of renewable electricity projects. Both of these incentives are designed for use by entities that pay Federal taxes and are subject to strict treatment under both the Internal Revenue Code and Generally Accepted Accounting Principles. These attributes have major implications for who utilizes the incentives and how projects are developed. Because they do not pay Federal income taxes, entities like municipal utilities and cooperative utilities cannot currently monetize these tax credits. For regulated utilities, the Internal Revenue Service requires that any ITC benefits be normalized[g] for ratemaking purposes. The net result of these nuances is that independent developers have played an outsized role in the deployment of wind and solar relative to previous technologies.

In December 2015, the ITC and PTC were both extended by 5 years through 2021 and 2019, respectively, with each tax credit on a different declining schedule. Solar system owners have primarily claimed the ITC, while wind power, which has higher capacity factors and lower capital costs, has benefitted from the PTC (Figure 3-4). A recent National Renewable Energy Laboratory (NREL) study estimates that the December 2015 extension of the ITC and PTC could result in an additional 53 GW of renewable electricity capacity by 2020 as compared to a case with no tax credit extensions, corresponding to 540 million metric tons of avoided CO_2 cumulatively by 2030, again compared to the no extension case.[46]

State RPS policies are also key drivers of renewable energy growth. Twenty-nine states have renewable or alternative energy portfolio standards that require utilities or other electricity providers to meet a minimum portion of load with qualifying forms of renewable energy**Error! Reference source not found.**.[47] Of the 230 terawatt-hours (TWh) of total non-hydro renewable electricity generation growth since 2000, over half (or 130 TWh) was to meet RPS mandates.[48]

Figure 3-5. State RPS Policies, August 2016[49]



[g] Normalization requires that a tax credit be realized across the life of an asset, instead of immediately.

Twenty-nine states and the District of Columbia have an RPS, and an additional eight states have a renewable portfolio goal; some include extra credit for solar or customer-sited renewables or include nonrenewable alternative resources. The RPSs or renewable portfolio goals are key drivers of renewable energy growth.

RPS rules vary from state to state, each with different targets, timeframes, and sometimes specific carve outs for solar or distributed generation (DG). Almost half of the mandated renewable energy capacity is located in California, "reflecting the rapid and recent build-out of renewable capacity to meet 2020 RPS targets, including the completion of a number of large utility-scale PV projects."[50]

In addition to state-level RPSs, some states have instituted electricity resource standards that set requirements for "clean" or "alternative" energy, which include not only renewables, but also certain non-renewable technologies, such as nuclear power and coal with CCUS. These are sometimes referred to as Clean Energy Standards (CESs). States that have implemented these include Colorado, Michigan, Illinois, New York, Ohio, Pennsylvania, and Utah.[h] There have been proposals for a Federal CES introduced in previous Congresses.

Renewable Energy Certificates (RECs) are tradeable certificates used to demonstrate and verify the use of renewable electricity in the United States, usually to meet state RPSs and sometimes to meet voluntary renewable goals. While generated concurrently with renewable electricity, RECs can be traded separately from the underlying electricity. While requirements for eligible resources vary from state to state, one REC is issued for each MWh of electricity generated from an eligible renewable energy resource. By obtaining and retiring (i.e., preventing further trading of) a REC, a utility or customer can claim it for compliance with an RPS or for voluntary purposes. REC tracking systems, available throughout the country, ensure that no claims on this renewable energy are double counted. In 2015, over 210 million RECs were projected to be generated to meet state RPS requirements.[51] An additional 78 million voluntary RECs were generated and retired for voluntary purposes by residential and commercial customers.[52]

Analysis indicates that new renewable electricity resources that were used to meet all state RPS obligations totaled 5,600 MW of capacity additions, as well as 98 TWh of generation in 2013.[53] One life-cycle GHG emissions analysis indicates that this new renewable electricity generation helped to avoid 59 million metric tons of CO_2 equivalent in 2013.[54] These policies are commonly highlighted by states as having strong potential to create jobs.[55] A 2016 study estimated that RPSs created 200,000 gross domestic renewable energy jobs in 2013.[56]

In order to fully realize the potential emission reduction benefits of high levels of zero-carbon variable energy resources, they must be integrated into the grid and provide grid services. Wind and solar plants are only currently required to provide grid services in certain regions.[i] Smart power converters for wind resources and smart inverters for solar resources could provide several services to assist in the integration.[57, 58, 59, 60, 61, 62, 63] CAISO, MISO, PJM, ISO-New England, and New York ISO are all making efforts

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[h] In 2016, two states, Illinois and New York, put policies in place to incentivize the continued operation of existing nuclear plants.

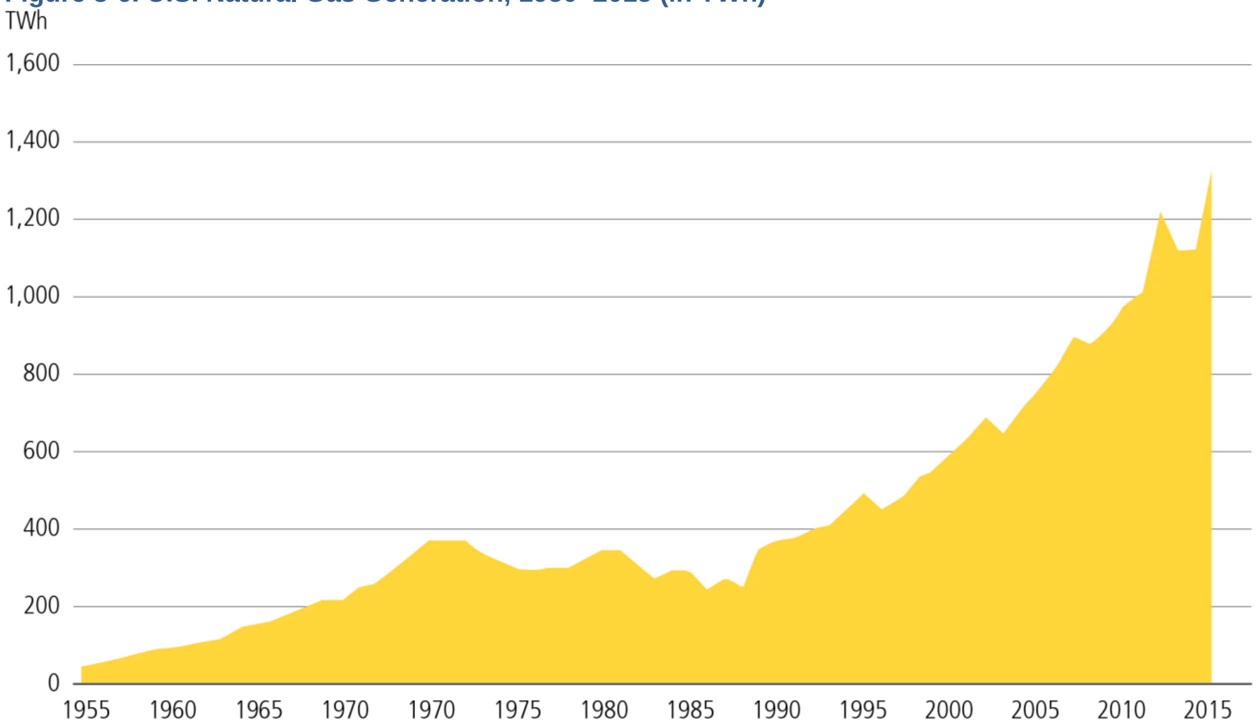
[i] In November 2015, the North American Electric Reliability Corporation (NERC) issued five general recommendations as part of its Essential Reliability Services Task Force Measures Framework Report, which that focus on the incorporation of these services into the design of variable generating resources in the future. Shortly thereafter, on February 18, 2016, FERC issued a Notice of Inquiry, Docket RM16-6-000, seeking comment on the need to reform its regulations for the provision and compensation of primary frequency response. Source: North American Electric Reliability Corporation (NERC), *Essential Reliability Services Task Force Measures Framework Report* (Atlanta, GA: NERC, November 2015), http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf ; Federal Energy Regulatory Commission (FERC), *Docket No. RM16-6-000, Essential Reliability Services and the Evolving Bulk-Power System-Primary Frequency Response* (Washington, DC: FERC, , February 16, 2016), https://www.ferc.gov/whats-new/comm-meet/2016/021816/E-2.pdf.

to integrate zero-carbon variable energy resources, for example, by developing or improving mechanisms to provide and support flexible ramping, the integration of flexible ramping products into their markets or incentives for reliable capacity.[64]

3.2.2.2 Natural Gas Generation: Lower-Carbon Flexible Baseload

Natural gas generation is projected to become the largest source of U.S. electricity in 2016, overtaking coal for the first time on an annual basis.[65] In 2015, natural gas–fired generation accounted for approximately 33 percent of total U.S. generation (see Figure 3-6 for natural gas generation in the United States from 1950 to 2015).[66] The availability of low-cost, domestic fuel; low capital costs; existing infrastructure; and relative generation flexibility have contributed to this increase. The shift towards natural gas generation resulted in 1,254 million metric tons of avoided CO_2 emissions from 2005 to 2014, or about 61 percent of total avoided emissions over that time period.[67] On a life-cycle basis, a new NGCC plant emits roughly 50 to 60 percent less CO_2 than a typical existing coal-fired power plant.[j, 68]

Figure 3-6. U.S. Natural Gas Generation, 1950–2015 (in TWh)[69]



Natural gas–fired generation has grown nearly continuously since the late 1980s.

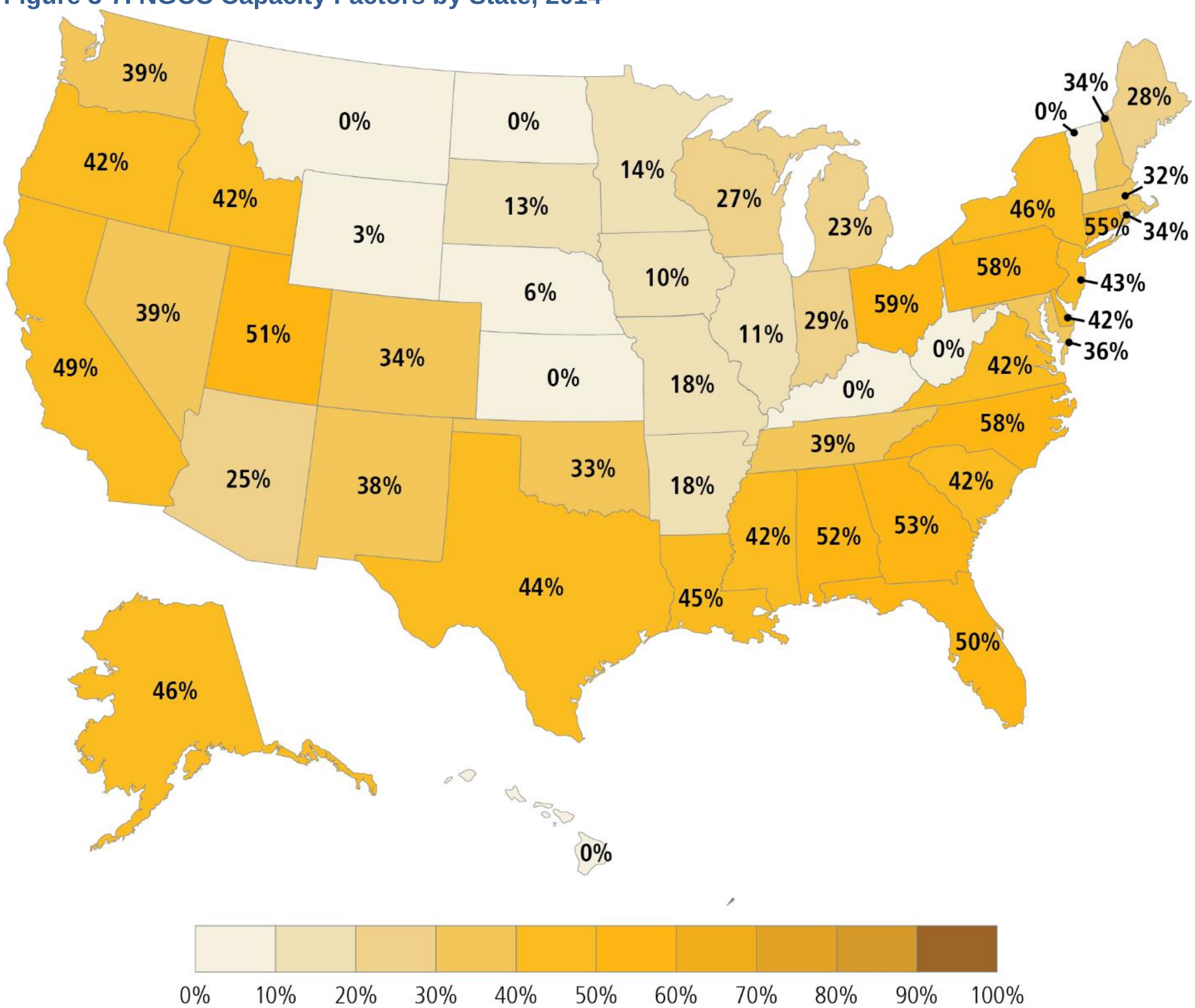
Natural gas combined cycle (NGCC) generators are very efficient, have unused capacity, and have significantly higher capacity factors than natural gas combustion turbines (CT) that contribute primarily to peak load and may only operate for a few hours a year (see Figure 3-8). Until recently, most NGCC units

[j] Life-cycle GHG emissions from natural gas–fired electricity generation are significantly lower than from coal-fired units. This is true even when accounting for methane emissions from natural gas and coal, a wide range of variability in the performance of equipment and operations, and the timing of impact to radiative forcing in the atmosphere. Furthermore, there are a number of ongoing policy efforts—including those outlined in Chapter VII of QER 1.1 (*Addressing Environmental Aspects of TS&D Infrastructure*)—that are contributing to further reducing methane emissions from natural gas, making natural gas's relative advantage even greater. These include recently finalized regulations by the Environmental Protection Agency (EPA) and Department of Interior, the EPA’s voluntary Methane Challenge Program, and several new programs at DOE to help improve quantification of methane emissions and expand related R&D.

were utilized for intermediate and peak loads, rather than baseload. Because natural gas prices have been low for a sustained period, and because NGCC plants retain some of the flexible characteristics of CTs, and operate at a higher efficiency and lower cost; these units are now often used for baseload power.

A CT's short startup times and fast ramp rates makes it essential for maintaining grid reliability, absent affordable grid-scale storage. Capacity factors for CTs are quite low (generally below 10%) but when operating, they can be significant contributors to conventional air pollutants.[70] Single cycle gas turbines can go from cold startup to 100 percent output in 7-11 minutes; in contrast, coal-fired units ramp on the order of hours, and doing so incurs increased O&M costs.[71] NGCC ramp rates fall somewhere in between, and some NGCC units can ramp to full rated power in less than 30 minutes.[72] This flexibility makes CTs useful in complementing variable generation, especially for solar, because it complements the high peaks associated with solar generation and allows for load following. Some states rely on CTs more regularly than other locations, most notably Texas, Louisiana, Wyoming, New Hampshire, Maine, and Rhode Island all have CT capacity factors greater than 20 percent.[73]

Figure 3-7. NGCC Capacity Factors by State, 2014[74, 75]



Capacity factors of NGCC plants all generally increased across the United States between 2010 and 2014, and many states have constructed or are planning to construct new NGCC plants after 2014. Significant potential exists to further increase generation from NGCCs in most states. In the figure, "0%" represents states with no NGCC capacity.

A recent study of the value of fast ramping gas for supporting variable renewables noted that, "…to date FRF [fast ramping fossil] technologies have enabled RE [renewable energy] diffusion by providing reliable and dispatchable back-up capacity to hedge against variability of supply...renewables and fast-reacting fossil technologies appear as highly complementary and…should be jointly installed to meet the goals of cutting emissions and ensuring a stable supply."[76]

It is also important to note that the changing generation mix and growing reliance on natural gas generation is also increasing the need for and value of demand response. ISO New England has, for example, developed a Winter Reliability Program to incentivize demand response, among other things, to protect natural gas customers during extreme cold weather events. Another example: New York ISO can activate demand response programs in the winter to increase reliability and decrease winter demand.[77] Demand response is discussed in greater detail in Chapter IV (*Ensuring Electricity System Reliability, Security, and Resilience).*

3.2.2.3 Coal, Natural Gas and Biomass Generation with Carbon Capture, Utilization, and Storage: Low-Carbon Baseload

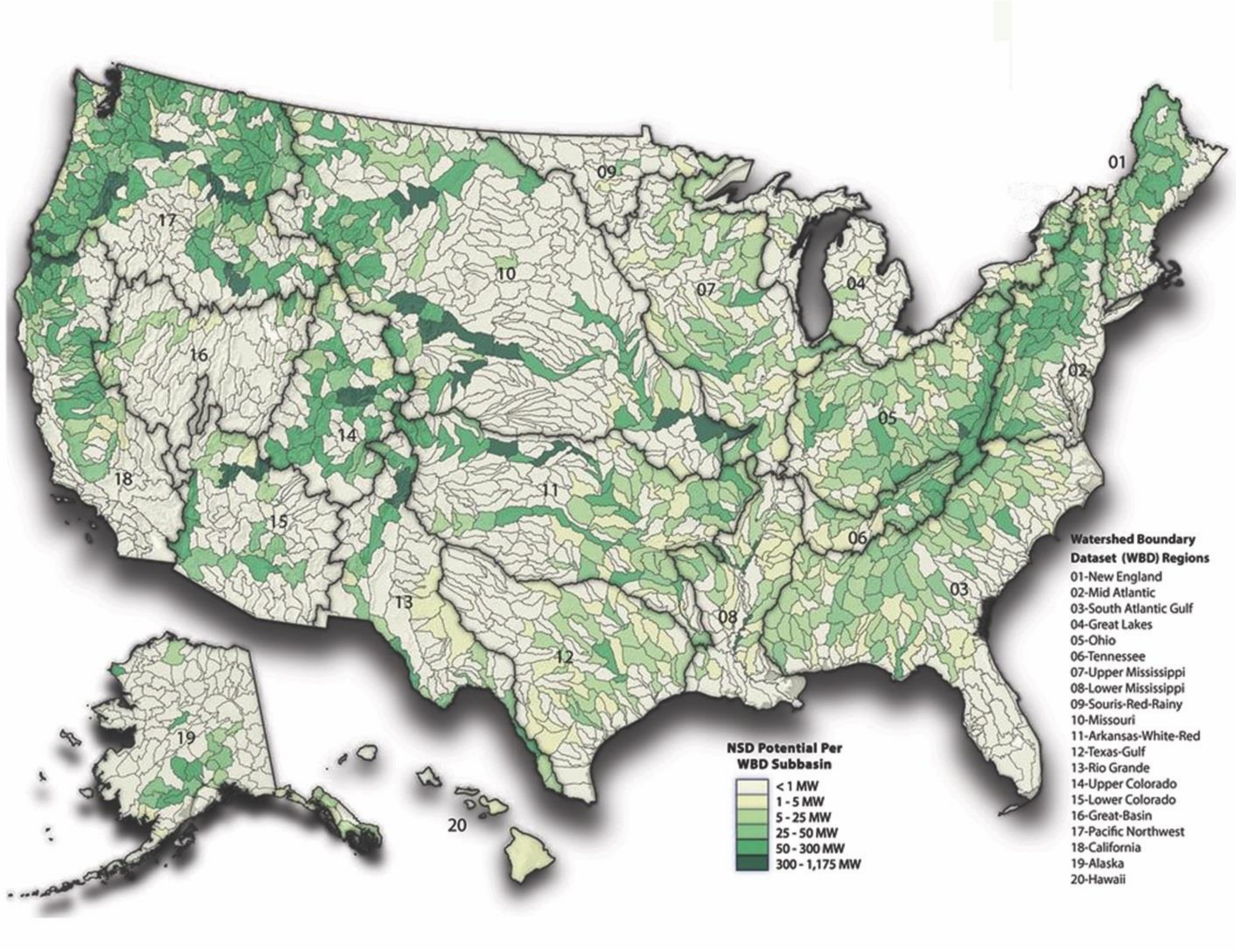
Though there is international consensus that CCUS for coal, natural gas and biomass generation will likely be required to realize the emission cuts needed to limit global warming,[78] investment in and deployment of CCUS technology lags behind other clean energy technologies primarily due to cost.[79] The United States is a global leader in enhanced oil recovery (EOR), with the largest CO_2 pipeline network in the world. CO_2 used for EOR has provided important revenue streams for CCUS projects but has been insufficient to support substantial deployment. Stronger CCUS deployment policies would help to provide the market certainty and financing needed for deployment and to develop supply chains, infrastructure, and ultimately, expanded private-sector investment in CCUS technologies. Continued research, development, and demonstration (RD&D) is also critical to improving performance and driving down the costs of CCUS technologies.

3.2.2.4 Hydropower: Zero-Carbon Baseload and Flexibility Resource[k]

In 2014, there was 79.6 GW of installed hydropower capacity from conventional facilities and 21.6 GW from pumped storage hydropower.[80] The average capacity factor of conventional hydroelectric generators was 40 percent. The technical resource potential for new hydropower developments is 65.5 GW, focused largely in the Pacific Northwest and Rocky Mountain West (Figure 3-9).[81] The technical resource potential for powering currently nonpowered dams is 12 GW, an increase of 15 percent over the existing fleet. This potential is focused mainly on the Mississippi River and its major tributaries, such as the Ohio and Red Rivers.[82] Upgrades and optimization for existing hydropower facilities could provide an additional 5.6 GW, or an 8 to 10 percent increase, of increased generation capacity through turbine efficiency improvements and facility optimization.[83] Hydropower comprises approximately 20 percent of U.S. zero-carbon generation.[84]

[k] Renewable energy sources that have zero emissions from generation can result in marginal emissions when evaluated through an life-cycle analysis; for example, see Department of Energy (DOE), *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source* (Oak Ridge, TN: DOE, 2016), https://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-10262016_0.pdf.

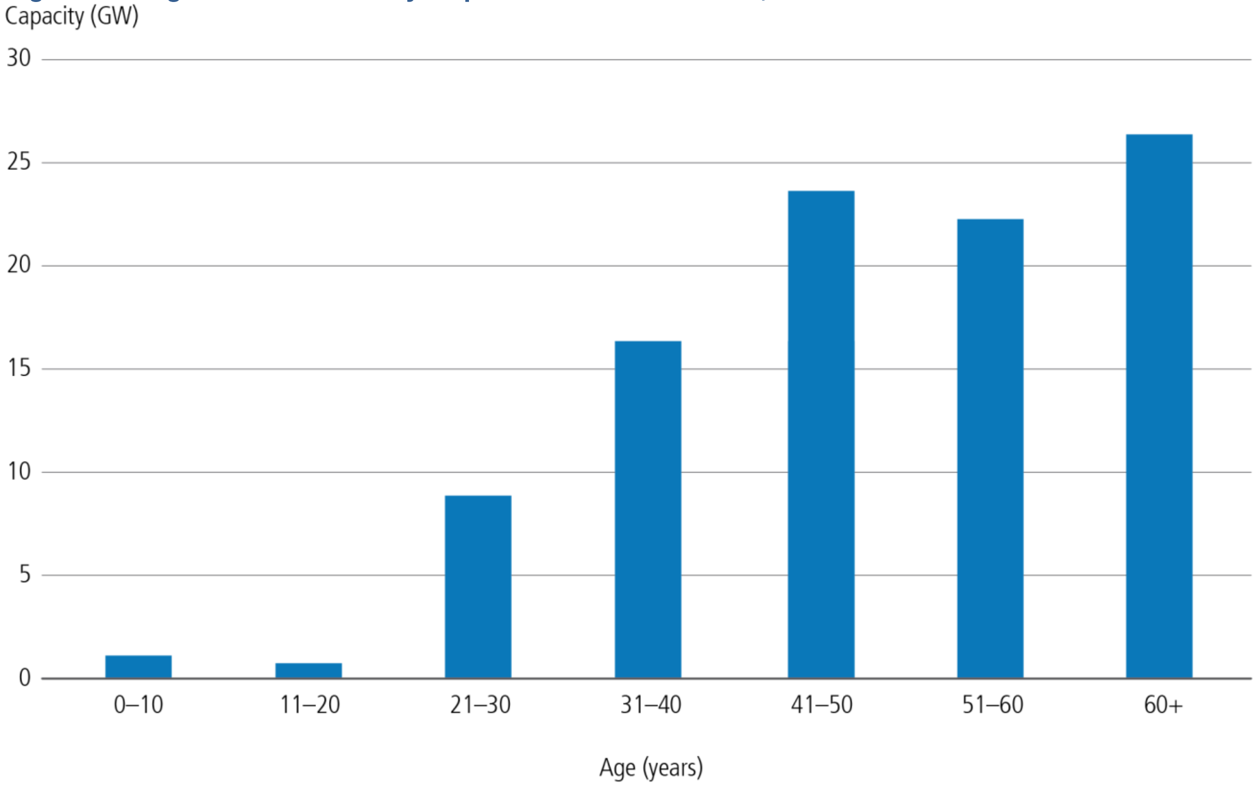
Figure 3-8. U.S. New Stream-Reach Development Potential by Sub-basin for the United States[85]



The technical resource potential for new hydropower developments is 65.5 GW, focused largely in the Pacific Northwest and Rocky Mountain West.

About half the U.S. hydroelectric fleet is over 50 years old since many large dams were built between the 1940s and 1960s (Figure 3-9).[86] However, with routine maintenance and refurbishment of turbines and electrical equipment, the expected life of a hydropower facility is likely to be 100 years or more.

Figure 3-9. Age Profile of U.S. Hydropower Generation Fleet, 2014[87]



About half the U.S. hydroelectric fleet is over 50 years old. Many large dams were built between the 1940s and 1960s.

There has been a renewed interest in the flexibility benefits that many hydropower projects can offer the grid, given the growth in variable renewable sources, especially wind. A recent report notes that about half of all installed hydropower capacity (39 GW) has high flexibility potential and could play an important role in low-cost integration of variable renewable generators.[88] Pumped hydropower storage can be used in peaking and balancing applications to maintain grid reliability and can play a balancing role in areas with high penetrations of VERs.

Large-scale hydropower projects are often difficult to finance due to high capital costs, lengthy permitting periods, and environmental concerns. While the prospects for building very large, new dams are low, there are other opportunities for hydropower to expand in the U.S. generation portfolio. Upgrading equipment at existing sites to expand capacity is likely to continue, and projects at currently non-powered dam sites could continue to advance. Modern low-impact, environmentally sustainable technologies, such as water-efficient and “fish-friendly” turbines, or run-of-river approaches have the potential to increase hydropower generation. Such upgrades and optimization for existing hydropower facilities could provide an additional 5.6 GW nationally, although individual facilities have seen generation increases of 35 percent with investment payback periods under 2 years.[89] Still, the amount of new hydropower capacity that is expected to come online over the near to mid-term is relatively modest when compared to wind and solar.

Over the next 10 years, existing FERC licenses will expire for nearly 250 hydropower projects. These expiring facilities total more than 16,000 MW, or nearly 20 percent of the existing installed capacity. It takes an average of 5 to 8 years to relicense an existing hydro project, with at least 3 years of pre-filing activity and then at least another 2 years after the application is filed. Only 2,198 dams are currently used for hydroelectricity—3 percent of the Nation’s total dams. (Other uses for dams include navigation, flood control, irrigation, and recreation.) Adding hydroelectricity to these preexisting dams would increase hydro generation by 15 percent, and these preexisting dams may not face as many siting constraints because some of the environmental impacts from dam construction have already been incurred. Such additions, combined with the ability to leverage and upgrade existing infrastructure at non-powered dams, which would increase hydro generation by 8 to 10 percent, provide significant opportunities to increase hydropower generation while reducing costs and environmental impacts.[90]

3.2.2.5 Biomass: Net-Zero Carbon Renewable Baseload and Flexibility Resource

Biomass fuels include a broad range of sources, including wood and wood-derived fuels, black liquor (primarily pulp residuals in the paper production process), municipal solid wastes, landfill gas, and others. If the emissions from combusting biomass are fully offset by the sequestration of CO_2 as the biomass is grown when accounting for the carbon flows in production and processing of the biomass, biomass electricity can be a low-carbon resource. Biopower plants are typically fully dispatchable and are generally dispatched as baseload generation if variable and fuel costs are low enough. Biomass sources can either be directly combusted, gasified to produce a synthetic fuel, or co-fired at a small amount (typically up to 10 percent heat content) with a conventional fuel such as coal.[91] In 2015, electricity generation from biomass across all sectors accounted for 11.3 percent of renewable electricity generation and 1.6 percent of total electricity generation in the United States. A significant number of biomass facilities are small enough that they can be located near their fuel sources. As such, nearly half of the electricity generated from biomass in 2015 was at industrial facilities outside of the electric power sector, such as pulp and paper mills. Generation from biomass across all sectors grew from 56 TWh in 2010 to 64 TWh in 2015, driven primarily from new capacity in southern states, such as Virginia, Florida, and Georgia.[92]

3.2.2.6 Geothermal Generation: Zero-Carbon Baseload and Flexibility Resource

Geothermal generators are baseload plants capable of providing valuable services to the grid, such as generation flexibility. Prior to 1980, geothermal generation remained below 5 TWh annually. Between 1980 and 1989, generation tripled to 15 TWh as new facilities came online. Much of the early growth in geothermal power was driven by Public Utility Regulatory Policies Act incentives, although this driver has declined over time as the avoided costs of utility generation have fallen. As of 2015, geothermal power continues to generate roughly 15 TWh of electricity annually, or roughly 0.4 percent of total U.S. electricity generation.[93, 94] Challenges in exploring new “blind” hydrothermal resources and long drilling times for production wells have led to increased uncertainty for investors in large geothermal projects. Additionally, tax credits that are only extended for short periods of time do not take into account the long lead time of geothermal project development, scarcity of power purchase agreement opportunities, or need for transmission infrastructure. Current ancillary service compensation models in areas with most geothermal development do not provide sufficient revenue to warrant the increased operational and control retrofitting expenses. If appropriately valued, the services a geothermal plant can provide include regulation, load following, spinning reserves, nonspinning reserve, and replacement or supplemental reserve.[95]

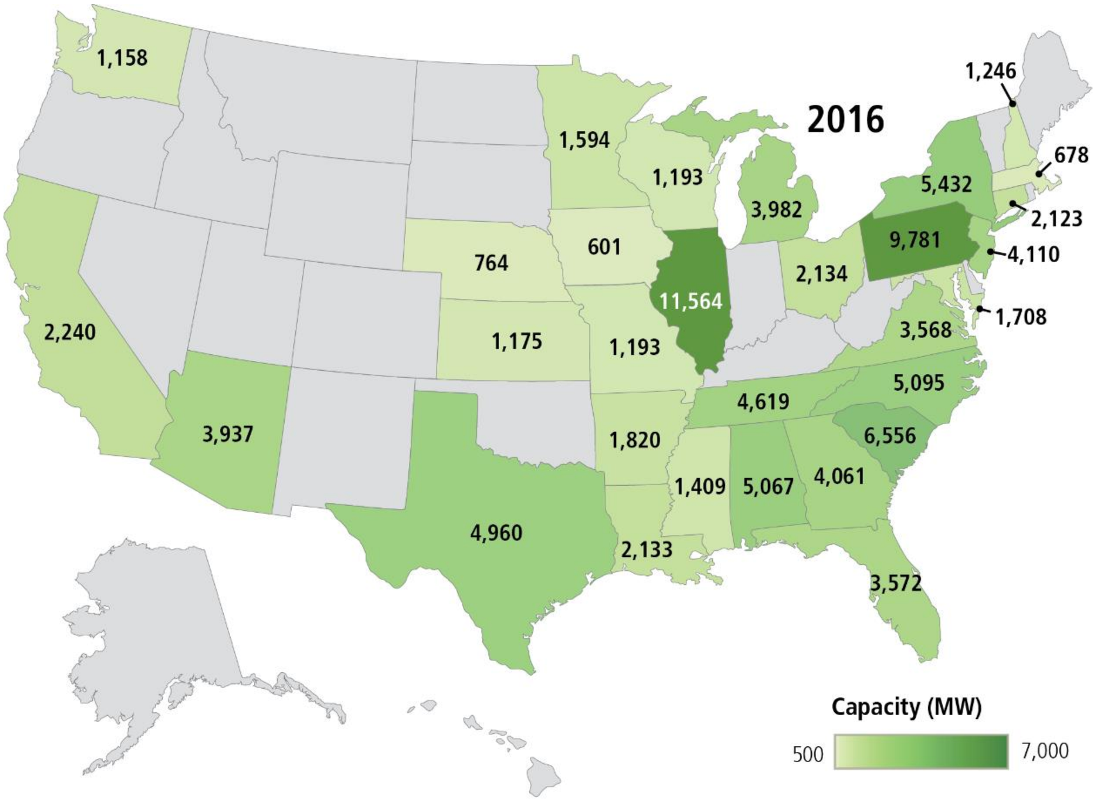
3.2.2.7 Nuclear Generation: Zero-Carbon Baseload

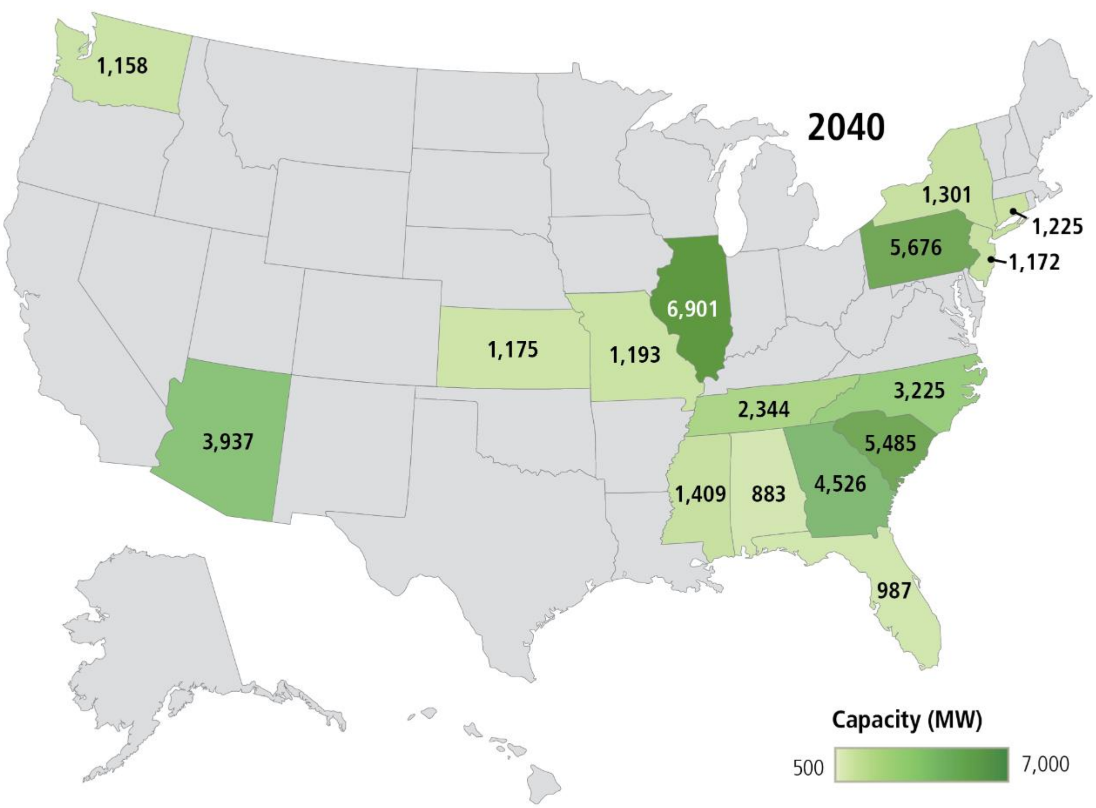
Nuclear generation comprises 60 percent of the Nation’s current zero-carbon generation.[96] The current operating nuclear power fleet consists of approximately 54 GW of generating capacity in regulated markets and 45 GW in restructured electricity markets.[97] Of the 99 operating nuclear reactors in the United States, so far, 80 have been approved to (and plan to) operate for 60 years, while another 9 currently have applications under review by the Nuclear Regulatory Commission (NRC).[98][l] The timeline for these units to reach the end of their 60-year license is as follows: 6 units between 2029–2030; 27 units between 2031–2035; 15 units between 2036–2040; 20 units between 2041–2045; and 12 units between 2046–2050.[99] Forty-eight units will reach the end of their licensed lifetime by 2040, the timeframe covered by QER 1.2. (Figure 3-10)[m, 100] Without renewals to 80 years, there will be a significant loss of zero-carbon generation starting in the 2030s. Also, if these plants were to all request a license renewal to 80 years, it would represent a significant additional workload for NRC staff and commissioners. Two plants, Surry Power Station and Peach Bottom Nuclear Generating Station, have announced intentions to seek subsequent license renewals, and others are also expected to do so.

[l] Diablo Canyon 1 and 2 are under review, but PG&E has announced it will withdraw the application

[m] These are the end dates with first license renewal.

Figure 3-10. Current and Projected Nuclear Capacity Assuming No Subsequent License Renewals[101, 102]





The top map in the figure shows U.S. nuclear power capacity (in MW) by state in 2016 (as of December 15, 2016). The bottom map shows what the U.S. nuclear power capacity by state would be in 2040 (December 31, 2040), assuming that all reactors, except those that have already specified closure dates, shut down at the expiration of their currently approved licenses.

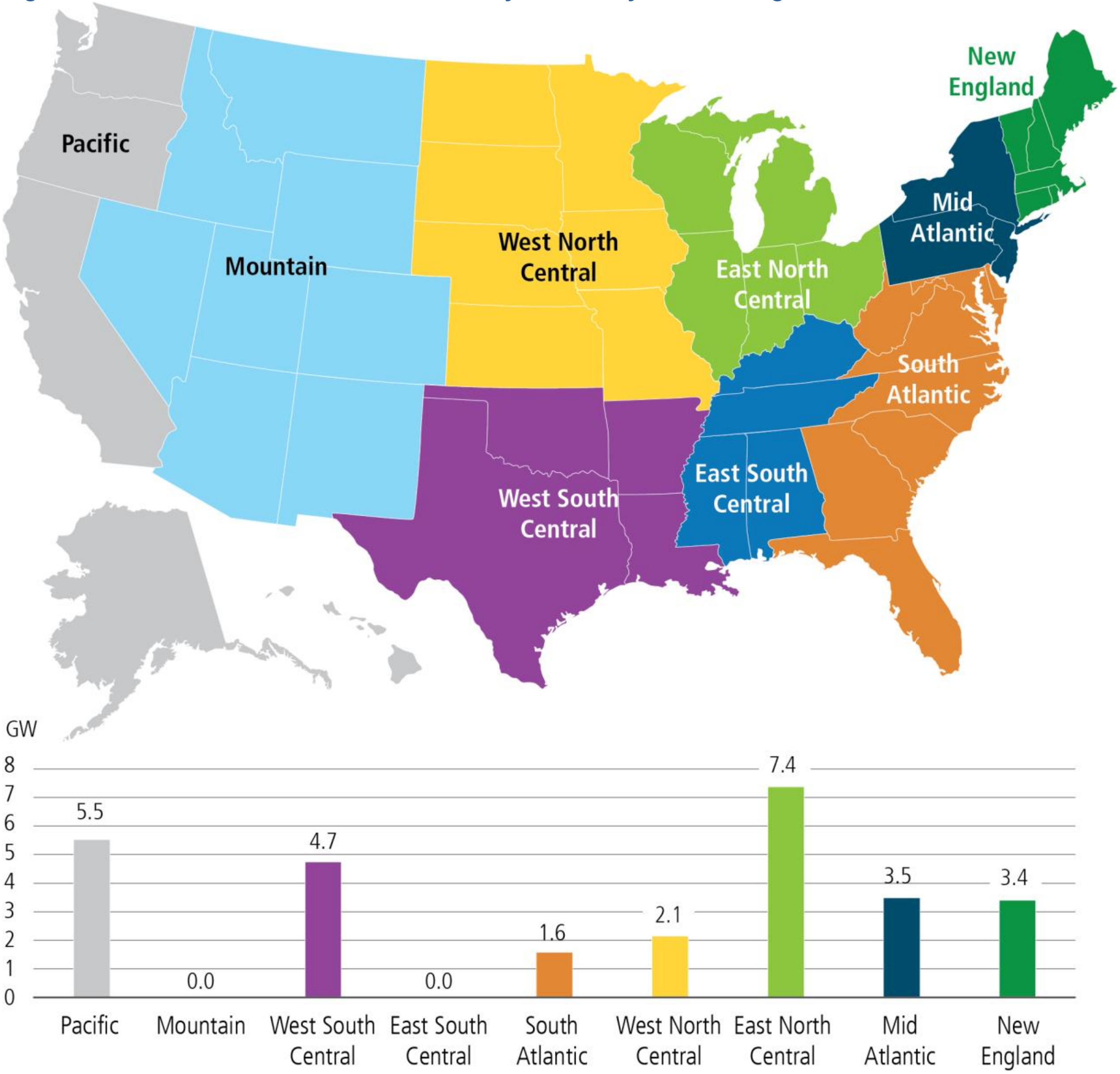
While estimates of the total amount of at-risk capacity vary, one recent analysis suggests that the capacity of retired or at-risk nuclear power plants by 2030 is about 28 GW, a little over one-quarter of U.S nuclear plant capacity; at-risk plant capacity varies by region, with the East North Central most affected (Figure 3-12).[103] Several nuclear power plants, particularly those with single units, face large recurring fixed costs. Some of these costs are due to post-Fukushima requirements, but many are simply the costs of operation, such as security, salaries, etc. Several plants have also needed large capital expenditures; faced with these significant costs, plant operators/owners have chosen to shut them down. Since 2012, when 104 reactors were operating, six units totaling 4.7 GW have shut down earlier than their licensed lifetime. Two retirements, San Onofre and Crystal River, have been driven by mechanical failures that were deemed too costly to repair; the others were market decisions. As of December 2016, ten other units totaling 8.6 GW of capacity have announced plans to close in the next decade (though six of these units may not close because of recent state actions); eight of those closures, with the exception of two units at Diablo Canyon, would occur prior to the expiration of the unit's existing licenses. Seven of the announced retirements, all those except Oyster Creek and Diablo Canyon, were attributed to market conditions.

In addition to plants with high recurring fixed costs, post-Fukushima, market structures have had significant impacts on the economics of nuclear generation. In states with restructured electricity markets, nuclear operators have found it to be increasingly difficult to compete under today's market conditions where electricity demand is flat or declining, natural gas prices and capital costs for new generation are low, wind and solar costs are declining and state policies favor renewable generation. There are however, new nuclear reactors under construction in vertically integrated markets. Watts Bar 2 entered service in Tennessee in 2016, and four additional reactors are under construction in Georgia and South Carolina that are projected to enter commercial operation in the 2019–2020 timeframe.

In 2016, two states, Illinois and New York put policies in place to incentivize the continued operation of nuclear plants. The New York Public Service Commission finalized its Clean Energy Standard (CES) on August 1, 2016, which contains a 50 percent renewable target by 2030, along with zero-emission credits (ZECs) for nuclear plants. The goal of the ZEC policy is to provide revenue support for three plants that had been at risk for premature retirement: Ginna, Nine Mile, and FitzPatrick. According to analysis from UBS, the ZEC policy would essentially guarantee revenue-positive operations for the three plants through a stable level of compensation.[104] Illinois enacted a similar policy as part of comprehensive energy legislation in December 2016.

The Secretary of Energy's Advisory Board Task Force on Nuclear Energy issued a report describing initiatives that would lead to a significant deployment of nuclear power in 2030–2050 timeframe. It outlines programs and efforts for both new and existing nuclear power and also advanced reactor technologies that are not based on traditional light-water reactor designs.[105]

Figure 3-11. Nuclear Units at Risk or Recently Retired by Census Region[106]



Across the country, over 28 GW of nuclear generating capacity is at risk or recently retired, most of which is in the East North Central region.

It is important to weigh the costs of nuclear generation compared to other zero carbon generation and to low-carbon natural gas generation to determine the relative value of at-risk nuclear generation units. A recent analysis estimated the "revenue gap" – the cost of incentives for keeping certain nuclear units running – for a discrete but representative set of nuclear power generating units.[107] DOE then analyzed the carbon emissions benefits of keeping this set of plants open by using a social cost of carbon of $41/metric ton. Assuming that all generation from retiring nuclear plants in this discrete set would otherwise be replaced with gas generation, keeping all but one of the nuclear units open would have higher benefits than costs. DOE's analysis only looked at the carbon benefits of at-risk generators; there are other, non-carbon benefits of retaining existing nuclear power, including jobs, reliability, and economic development benefits as well. Nuclear plants generally only shut down for maintenance activities, and forced outages are very rare, The carbon intensity of the replacement generation for retiring nuclear plants is a key unknown. If the replacement generation is less carbon intensive than natural gas, fewer plants would pass this cost-benefit test. If the replacement generation is more carbon intensive, more plants would pass this cost-benefit test. It is possible that some coal may replace nuclear generation in specific regions. When analyzing the impacts of premature nuclear retirements on power generation in the state, a state of Illinois report considered a scenario in which 80 percent of the replacement generation was coal.[108] Other analysis concludes that roughly 75 percent of the at-risk nuclear generation nationwide would be replaced with fossil generation, largely powered with natural gas.[109]

Sufficiently favorable revenue, technology performance, policy, and market conditions enable financing for clean electricity systems. To accelerate the deployment of clean systems, federal policies can address the barriers discussed in this section and may create the conditions under which more clean resources can obtain financing. These policies include mechanisms that increase the financial return on clean energy projects, improve the financial profile of entities that participate in clean energy, or allow greater access to capital.

3.2.3 Decarbonization via Distributed Energy Resources

DERs represent a wide range of generating or load-reducing technologies and programs that reside on a utility's distribution system or on the premises of an end-use consumer. DERs can help reduce carbon emissions by providing electricity from low- or zero-carbon emitting technologies and by reducing demand. In addition, DERs can also impact how much, and when, electricity is demanded from the grid, thereby supporting improved grid flexibility and load balancing. DERs provide system reliability challenges and opportunities that are discussed in detail in Chapter IV (*Ensuring Electricity System Reliability, Security, and Resilience).* DERs also provide business and consumer challenges and opportunities that are discussed in detail in Chapter II (*The Electricity System: Maximizing Economic Value and Consumer Equity)*.

Technical definitions of DERs vary, but for purposes of QER 1.2, DERs are defined as DG, distributed storage, and demand-side management, including energy efficiency and DR. All DERs can reduce carbon and other environmental impacts, but they do so in different ways. Energy efficiency provides environmental benefits by avoiding generation, transmission and distribution and their associated environmental impacts. Clean distributed generation provides environmental benefits by displacing higher-emitting generation. Demand response and distributed storage enable a cleaner grid by providing grid services with lower environmental impacts than other options for providing such services. The infrastructure needed to enable DERs includes technologies that enable DR and improved demand control (e.g., smart meters, building automation systems, smart appliances, and direct load control technologies); highly efficient equipment and envelopes; DG systems (e.g., natural gas– and biomass-fired combined heat and power [CHP], waste heat recovery, backup generation, rooftop solar PV, small-scale wind power, geothermal); and distributed storage systems (e.g., vehicle to grid,[n] batteries, thermal, flywheels). [o]

Some DERs, such as distributed solar PV and energy efficient equipment, can have a significant impact on system load, but may not be under the direct control of grid operators. Other technologies, such as

[n] Vehicle-to-grid configurations enable electricity to flow from the battery of a plug-in electric vehicle (PEV) to the grid and back to the vehicle.

[o] Not all DERs are connected to a utility electric grid or can be controlled by grid operators. For example, resources deployed on some microgrids and CHP systems are still DERs, despite lacking a grid connection. Note that the Energy Information Administration considers DERs that are *not* connected to the grid as "dispersed generation" rather than "distributed generation." See Energy Information Administration (EIA), *Modeling Distributed Generation in the Buildings Sectors (*Washington, DC: EIA, August 20130), https://www.eia.gov/forecasts/aeo/nems/2013/buildings/.

residential hot water heaters, have the potential to serve as DERs as DR measures, but technologies enabling this resource have low penetration or are still nascent. Also, opportunities to improve energy efficiency and usage of DERs vary by climate and household demographics, so tailoring programs to local needs is important. The West and South census regions, for example, where average household electricity consumption is higher than other regions,[p] are both experiencing high population growth rates.

Developments in DER and information and communications technologies (ICT) can support an electric grid capable of much greater flexibility in managing both supply and demand. This can offer multiple value streams (e.g., energy, capacity, reactive power, frequency support, deferred utility capital expenditures, energy security, and avoided emissions). Smart grid technologies can also enable improved demand-side management and reduce carbon emissions. Analysis that sought to quantify the CO_2 benefits of 100 percent penetration of smart grid technologies by 2030 using nine different mechanisms suggests a possible 12 percent direct reduction in emissions (through implementation of the smart grid technologies that directly affect electricity and CO_2 emissions) and a 6 percent indirect reduction in emissions (translating the estimated cost savings in energy and/or capacity into their energy and carbon equivalents through purchase of additional cost-effective energy efficiency).[110] Transactive energy controls, smart charging of plug-in electric vehicles (PEVs), and other approaches to controlling load in response to grid conditions can contribute to both direct and indirect reductions in emissions. Table 0-2 shows the value of the various mechanisms analyzed.

Table 0-2. Potential Reductions in Electricity-Sector Energy and CO_2 Emissions in 2030 Attributable to Smart Grid Technologies[111]

	Reductions in Electricity-Sector Energy and CO_2 Emissions[a]	
Mechanism	**Direct (%)**	**Indirect (%)**
Conservation effect of consumer information and feedback systems	3	-
Joint marketing of energy efficiency and DR programs	-	0
Deployment of diagnostics in residential and small/medium commercial buildings	3	-
Measurement and verification for energy efficiency programs	1	0.5
Shifting load to more efficient generation	<0.1	-
Support additional electric vehicles and plug-in hybrid electric vehicles	3	-
Conservation voltage reduction and advanced voltage control	2	-
Support penetration of renewable wind and solar generation (25 percent RPS)	<0.1	5
Total reduction	**12**	**6**

The combined impact of nine smart grid mechanisms, assuming 100 percent penetration of smart grid technologies by 2030, is a 12 percent reduction in annual U.S. electricity-related CO_2 emissions from direct

[p] Electricity use for space heating is particularly high in the South census region. The South, and to a lesser extent the West, census regions also have high cooling loads.

effects, and a 6 percent reduction from indirect effects.[q] Assumes 100 percent penetration of the smart grid technologies.

ICT technologies are enabling greater energy efficiency and its concomitant environmental benefits, in two important ways. First, they automate energy efficiency: for example by shutting off lights, devices, and appliances when they are not needed; or adjusting HVAC depending on the time of day. Second, they enable more advanced evaluation, measurement and verification (EM&V, sometimes referred to as EM&V 2.0) of energy efficiency programs and incentives, improving their effectiveness and quantification, and enabling efficiency providers to be accurately compensated for providing energy efficiency benefits, including environmental benefits. ICT technologies enable networks that connect the electric grid from end to end, facilitating communications throughout the system. Example applications include advanced sensors and controls in buildings to detect and eliminate energy waste and advanced metering infrastructure (AMI) that enables automated response to electricity prices via settings (e.g., for thermostats) by consumers. These technologies can improve the environmental performance, reliability, resilience, flexibility, and efficiency of the electricity system through real-time monitoring and control of grid systems.

3.2.3.1 Energy Efficiency: Environmental Benefits and Consumer Savings

End use energy efficiency is a range of measures that provide end users the same services (such as light and air conditioning) with less energy. Energy efficiency has multiple benefits. All electric generation, transmission and distribution has some impact on the environment. Energy efficiency avoids all of these environmental impacts. It emits no GHGs, air or water pollution. It has no impact on land use. It requires no siting, permitting or decommissioning. Energy efficiency also saves consumers money, making it the most cost-effective decarbonization option. Energy efficiency programs and savings are discussed further in Chapter II (*The Electricity System: Maximizing Economic Value and Consumer Equity)*.

DOE's Appliance and Equipment Standards Program[112] has served as one of the Nation's most effective policies for improving energy efficiency. The program implements minimum energy conservation standards for more than 60 products that consume about 90 percent of home energy use, 60 percent of commercial building energy use, and 30 percent of industrial energy use.[113] Since 2009, the United States has issued 40 new or updated standards to make appliances, buildings, and equipment more efficient. These standards are projected to reduce carbon emissions between 2009 and 2030 by over 2.5 billion metric tons, save consumers $557 billion on utility bills, and reduce primary energy consumption by 42 quadrillion British thermal units (Btus).[r, 114] This number is expected to grow to 3 billion metric tons with standards published through January 2017.[115] For example, in January 2016 DOE finalized efficiency standards for commercial air conditioning and heating equipment, which is projected to avoid 77 million metric tons CO_2 by 2030.[116] Today, a typical household saves about $319 per year off their energy bills as a result of these standards, and as people replace their appliances with newer models, they can expect to save over $460 annually by 2030.[117] In addition to minimum efficiency standards for appliances, the Environmental Protection Agency (EPA) leads ENERGY STAR, a voluntary labeling program designed to

[q] The direct reductions were calculated for the mechanisms that affected electricity and CO2 emissions directly through implementation of the smart grid technologies. Indirect reductions are derived by translating the estimated cost savings in energy and/or capacity into their energy and carbon equivalents through purchase of additional cost- effective energy efficiency. This can represent a policy decision to reinvest the savings to purchase additional more cost effective energy efficiency and renewable resources.

[r] These savings numbers are as of December 2016. Appliance and equipment standards continue to be issued and updated. Refer to the Appliance and Equipment Standard Program website for updated information (http://energy.gov/eere/buildings/appliance-and-equipment-standards-program).

help businesses and individuals save money and avoid pollution with energy-efficient products. ENERGY STAR labels appear on major appliances, office equipment, lighting, home electronics, new homes, and commercial and industrial buildings and plants. The ENERGY STAR program saved American consumers an estimated $24 billion in energy costs in 2012 alone.[118]

Buildings, which last for decades, account for 76 percent of electricity consumption and 40 percent of GHG emissions in the United States.[119] Recent analysis shows that in states consistently adopting the most recent versions of the model building energy codes, homeowners, building owners, and tenants are projected to save $126 billion on energy bills and reduce carbon emissions by over 841 million metric tons cumulatively between 2010 and 2040 if energy codes continue to be strengthened.[120] Many of the high-efficiency technologies, building envelope designs, and energy management practices that enable significant energy savings and GHG reductions beyond today's building codes have been demonstrated and are commercially available. While continued developments in building design and technology improvements in key building components and systems have led to large efficiency gains, there remains a large gap between the efficiency of the existing building stock and what is possible using technologies available today.[121] Policies or programs could help overcome market and behavioral barriers that are limiting deployment. Using existing technologies and building design and construction practices, builders are able to design homes that are up to 50 percent more efficient than typical new homes,[122, 123] and these can provide consumers with monthly energy savings up to $100.[s, 124, 125] The National Institute for Standards and Technology has completed a demonstration at its Net Zero Energy Residential Test Facility; total present value energy costs for a net-zero energy home were more than $40,000 lower than a new home built to the comparable minimum code.[126] Recent studies demonstrate that construction costs for net-zero energy buildings in the commercial sector are capable of falling within the same range as conventional new construction projects.[127, 128] It is worth noting that, when attempting to calculate the incremental construction cost of a net-zero energy building[t] compared to a conventional building, additional factors, such as continued operational savings, increased occupant comfort, and increased building value, should also be considered.

The industrial sector is responsible for approximately 26 percent of electricity-related CO_2 emissions.[129] Electricity productivity in the industrial sector (measured in kWh per dollar of output produced) has improved rapidly over the last 15 years,[u] and continued improvement will depend on persistent attention to efficiency. In regions where the emissions intensity of central electric generation is high, switching to CHP will have the biggest emissions impact. DOE estimates that there is technical potential for roughly 241 GW of CHP capacity in the United States, including industrial and commercial CHP as well as waste heat to power.[130] Since most of industrial CHP is fueled by natural gas,[131] however, either fuel-switching to decarbonized fuels or a transition away from CHP would be needed in the long term to more fully decarbonize the industrial sector.

3.2.3.2 Distributed Generation, Distributed Storage, and Demand Response

In recent years, there has been significant growth in DG, particularly rooftop solar PV, which has been fostered by lower installation and hardware costs and supportive policies, such as net metering and self-

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[s] EPA's ENERGY STAR Certified Homes are typically 15 percent to 30 percent more efficient than the average new home, yet they can provide monthly energy cost savings of about $27–$93 to consumers. DOE's Zero Energy Ready Homes are at least 40 percent to 50 percent more efficient than typical new homes, yet they can provide consumers with monthly energy savings of about $30–$100. See citations in the main text for details regarding these estimates (endnotes 149–152).

[t] Zero-energy buildings are high-performance commercial and residential buildings that are so energy efficient, a renewable energy system can offset most or all its annual energy consumption.

[u] Electricity productivity, measured as dollars of GDP produced per kWh, nearly doubled between 1990 and 2014, while industrial electricity sales were flat.

generation tariffs and RPSs with set-asides or multipliers for DG. However, some states and utilities are adjusting their net metering policies as the distributed PV market grows. Net metering is a relatively simple policy, and as the distributed PV market has grown dramatically, many states are updating their incentive structures for distributed PV to more carefully account for changing electric system needs, transfers between ratepayer classes, and various benefit and cost streams. This is discussed in depth in Chapter II (*The Electricity System: Maximizing Economic Value and Consumer Equity)*.

Small-scale distributed electricity storage is becoming more widely available and can contribute to a clean electricity system by facilitating increased penetration of variable wind and solar resources. It can also reduce peak load, improve electrical stability, and reduce power quality disturbances. Distributed storage is also covered in greater detail in Chapter II (*The Electricity System: Maximizing Economic Value and Consumer Equity).*

Like distributed storage, demand response (DR) enables a cleaner grid by providing grid services with lower environmental impacts than other options for providing such services. If appropriately designed and resourced, DR enables utilities, grid operators, or other intermediaries to call for specific reductions in demand when needed; this could provide benefits in reducing peak load and supplying essential reliability services when increased variable energy resources are on the grid. At higher penetration levels of wind and solar (variable) energy resources, policies and regulations that enable greater penetration of demand response in grid services markets are likely to become increasingly important to enable a cleaner grid.[132] AMI enables time-based rates and facilitates the integration of distributed generation systems (e.g., solar), among other capabilities. More automated demand response capabilities will enable greater flexibility of demand-side resources, improved integration of variable renewable energy resources and easier valuation of their carbon emissions benefits, and enhance system integrity through greater area-wide knowledge. The most viable DR end-uses for VER integration are electric water heaters and furnaces, air conditioners and lighting with advanced controls, agricultural irrigation, and motor/compressor drives with variable frequencies.[133]

3.2.4 Increased Electrification is Essential for Decarbonization

Analyses that explore high levels of long-term GHG emissions reductions suggest that the increased electrification[v] of key end uses in transportation, buildings, and industry is one of three fundamental areas (in addition to decarbonizing electricity generation and adopting highly-efficient end uses) needed to achieve deep decarbonization.[134, 135] Multiple sectors of the economy have already begun to exhibit trends towards electrification. A continuing shift toward both decarbonization of the electric power system and electrification of end uses would help reduce GHG emissions economy-wide and provide a significant opportunity to avoid the GHG emissions associated with the direct use of fossil fuels without CCUS.[136] The level of GHG emissions reductions that can be achieved via electrification depends on a variety of factors, such as the carbon intensity of the electricity system; the efficiency of electricity generation, transmission, and distribution; energy efficiency improvements in end-use sectors; and the potential for fuel switching, which could include the use of hydrogen produced via electrolysis. Policies are needed to incentivize early technology adoption and to increase penetration of electrification in specific sectors, applications, and regions.

[v] In the context of the QER, electrification includes both using electricity itself to power end-use applications as well as using electricity to make intermediate fuels such as hydrogen.

3.2.4.1 Electrification of Buildings

Analysis demonstrates that increasing electrification of building end uses could help the United States reach deep economy-wide decarbonization.[137, 138, 139, 140, 141] The largest non-electric end uses for residential and commercial buildings are space heating and water heating. Electricity usage for space heating is currently increasing, and natural gas and other direct fuel usage are trending downward.[142] Advances in heat pump technology for both space heating and water heating have made heat pumps an economical and efficient choice. Heat pumps can be twice as efficient as electric resistance space heating. Currently, electrification of some end uses saves consumers money and/or saves energy in many parts of the country.[143, 144] Improving single-family detached homes with a package of fuel-switching efficiency upgrades[w] has the technical potential to save 450 trillion Btu per year of primary energy nationally, or about 3 percent of total primary energy used for electricity in the residential sector in 2015.[x, y, 145] This energy savings and the corresponding emissions reduction potential varies widely by state and region as a result of fuel choice, technology, and climate differences. With current technologies, assuming a 50 percent and a 90 percent cleaner grid than today,[146] the technical potential of the same set of upgrades for carbon emission reductions is 80 million metric tons and 120 million metric tons of CO_2 per year, respectively.[147] The emissions savings would not be as significant with the current generation mix of the U.S. power sector. As technologies continue to improve and to come down in price, both the economic and technical potential will increase.

3.2.4.2 Electrification of Industry

The industrial sector, perhaps more than any other, is a sector in which technological innovation is needed for decarbonization; in addition, systematic economic electrification for shifting from direct fuel use is technically more difficult and expensive for industry. Electrification is likely to be only partially viable for the industrial sector due to physical and economic reasons;[148] this would likely make the sector a high-value area for CCUS,[z] hydrogen, and biofuels to reduce carbon intensity.[aa] Conventional boiler use and process heating are two industrial end uses with meaningful technical potential for electrification. Fuel-fired boilers can be replaced with electric boilers and, depending on the industry, different electro-technologies are best suited to provide process heat. For example, electrolytic reduction, induction heating, resistance heating and melting, direct arc melting, and industrial process heat pumps can be used for process heating in the nonferrous metals (non-aluminum),[149] metal fabrication,[150] glass,[151] iron and steel,[152] food,[153] chemical,[154] and pulp and paper[155] industries, respectively.

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[w] List of upgrades considered in this package include (1) ductless heat pump (DHP) replaces gas boiler (100% displacement); (2) DHP replaces oil boiler (100% displacement); (3) DHP replaces propane boiler (100% displacement); (4) variable speed heat pump (VSHP) replaces air conditioner and gas furnace; (5) VSHP replaces air conditioner and oil furnace; (6) VSHP replaces air conditioner and propane furnace; (7) heat pump water heater (HPWH) 80 gallon replaces oil water heater (WH); 8) HPWH 80 gallon replaces propane WH.

[x] The current economic potential (NPV>0) to save primary energy with this package of measures is lower, but still significant at 252 trillion Btu per year.

[y] This accounts for the conversion losses of electricity generation and the transmission and distribution (T&D) line losses compared to direct fuel usage (e.g., natural gas, oil, and propane).

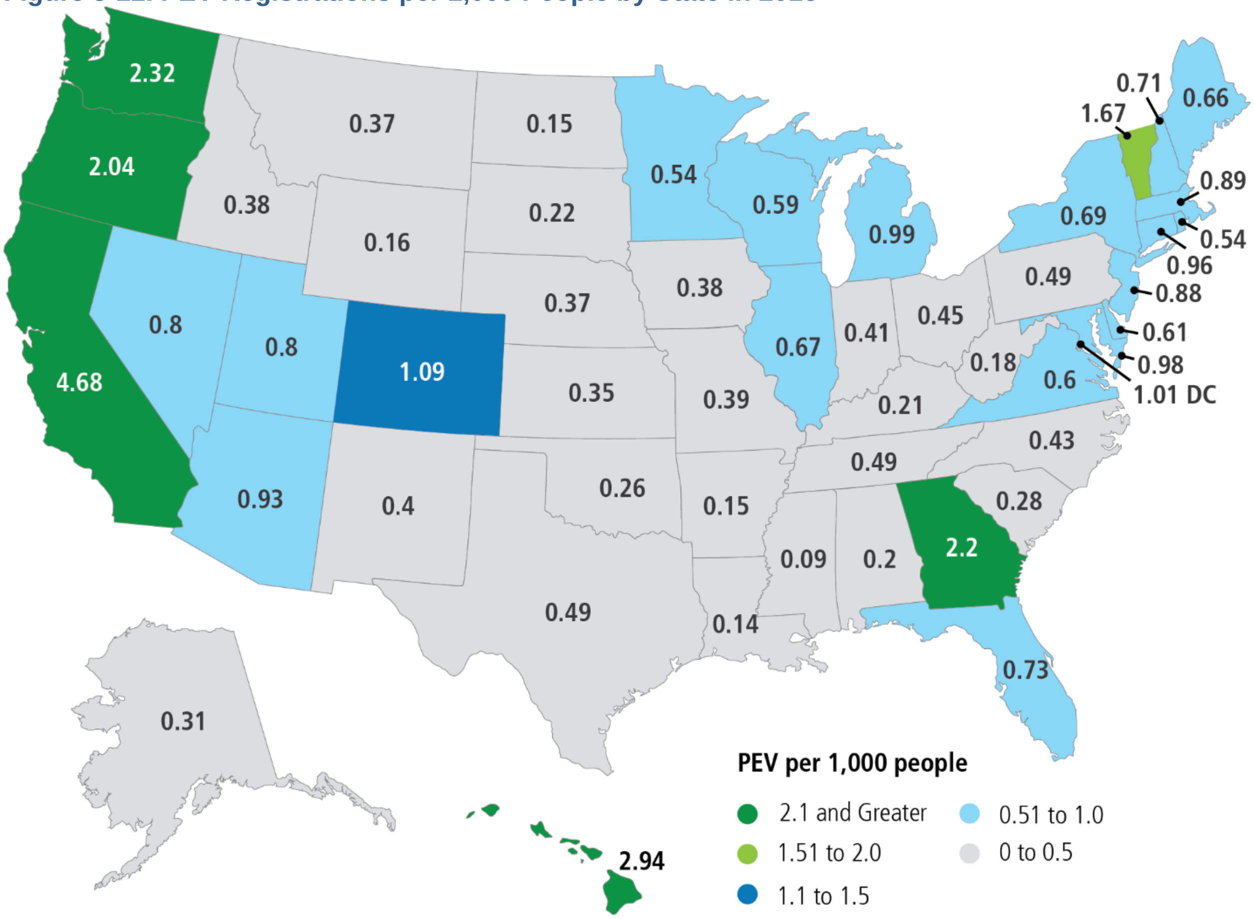
[z] Many industrial processes produce relatively pure streams of CO_2, making CCUS an attractive method for decarbonizing portions of the industrial sector. Industrial facilities represent a low-cost pathway for stimulating CCUS deployment, as capture from high-purity sources provides valuable early permitting, infrastructure deployment, and market opportunities; this, in turn, will lower the cost of capturing CO_2 from future industrial- and power-sector projects.

[aa] A significant fraction of energy consumption in industry goes to feedstock use and cannot be decarbonized through electrification. Several industrial processes have the potential to substitute materials for lower GHG options.

3.2.4.3 Electrification of Transportation

Many studies conclude that significant CO_2 emissions reductions are needed from the transportation sector for deep decarbonization; this will require widespread electrification of, or use of another non-emitting fuel by, the U.S. vehicle fleet.[156, 157, 158] In recent years, there has been a sharp increase in electric light-duty vehicle sales and electric vehicle miles traveled, but total PEV sales account for less than 1 percent of all light-duty vehicle sales.[159] Projections for future adoption of these vehicles vary and may be influenced positively by smart mobility trends, such as connected and automated vehicles and ride sharing. Electrification technologies are also being introduced into other segments of the transportation sector, such as larger vehicle classes and ground operations at ports and airports.

Figure 3-12. PEV Registrations per 1,000 People by State in 2015[160]

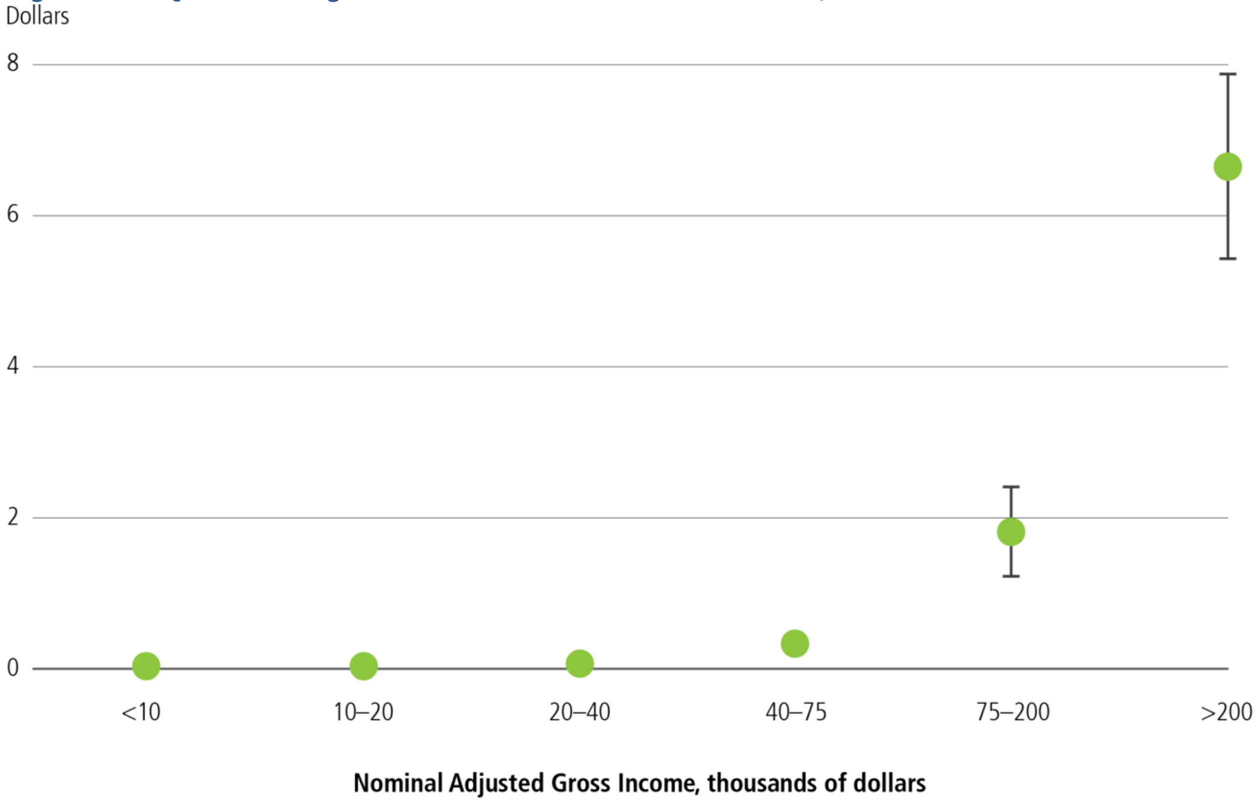


The concentration of PEV registrations varies by state, with the highest concentrations in California, Washington, Georgia, and Oregon.

When buying a new vehicle, however, one of the most important criteria for purchasers is the upfront vehicle price[161] and future fuel savings tend to be under-valued.[162, 163] Currently, the average price of new gasoline-powered cars is similar to that of comparable new PEVs with incentives.[164] In fact, with incentives, for some purchasers, the total cost of ownership over the lifetime of a vehicle can actually be lower for PEVs.[165, 166, 167] Incentives are still, however, important for deployment of PEVs. While battery costs have come down and are projected to continue to decrease with continued RD&D,[168] scaling up production alone will not be sufficient to lower the cost of PEVs to make them comparable to internal combustion engines without incentives and further technology cost reductions.[169]

A related issue: A recent study found that the current Federal tax credits for plug-in and alternative motor vehicles are being disproportionately utilized by vehicle owners in higher income brackets, as 90 percent of the qualified plug-in electric drive motor vehicle credits went to buyers in the top income quintile (Figure 3-13).[170] The state of California recently decided to increase the amount of the state's clean vehicle rebate for lower income purchasers and at the same time implement an upper income cap on eligibility.[171] Analysis of the California rebate, prior to the recent change, found that a progressive rebate system with an income cap would be less expensive but result in approximately the same number of PEVs sold.[172]

Figure 3-13. Qualified Plug-In Electric Drive Motor Vehicle Credit, 2009–2012[173]



The relationship between average credit per tax return per adjusted gross income category demonstrates that, historically, high earners are the group that derives the most financial benefits from the Qualified Plug-In Electric Drive Motor Vehicle Credit.

In the medium- and heavy-duty vehicle market, there are some commercially available PEVs, including battery electric transit, school, and shuttle buses, as well as other medium-duty vehicles, primarily delivery vehicles.[174] Although medium- and heavy-duty PEV purchase costs are higher than conventional vehicles, these PEVs have reduced operating and maintenance costs,[175] which may make them attractive to fleet operators if they can finance the initial purchase of the vehicle.

The availability and type of electric vehicle charging stations is another issue. Chargers vary dramatically in price and the amount of time it takes to charge the vehicle.[bb, 176] The United States currently has more than 40,000 publically accessible outlets at more than 14,000 charging stations (excluding private stations),[177] but continued increases in charging availability—especially deployment of advanced fast-charging stations—would support and incentivize widespread PEV adoption.[178] Research shows that available public fast charging reduces range anxiety and increases electric vehicle miles traveled.[179]

[bb] For example, Level 1 chargers at least 33 hours to charge 200 miles and typically $300-$1,500 dollars to install. Direct Current Fast Chargers take about 2 hours to charge 200 miles and cost $45,000, plus $23,000 on average for installation.

Developing a network of chargers along highways to include direct current (DC) fast chargers, and perhaps even 350-kW extreme fast charging, could enable PEV owners to use these vehicles for distance driving, as they might otherwise use a conventional vehicle.[180] Also, when workplace charging is available, employees are six times more likely to own a PEV, and those employees charge their vehicles at work.[181, 182]

There is a range of incentives and programs to expand PEV infrastructure. More than 20 state and Federal policies exist to incentivize the installation of PEV charging infrastructure (see Figure 3-12 for PEV registrations by state).[183] Also, in November 2016, the Federal Highway Administration announced 55 routes that will serve as a basis for a national network of alternative fuel and electric charging corridors spanning 35 states and nearly 85,000 miles.[184] Those corridors are designated as "sign-ready," meaning that routes where alternative fuel and charging stations are currently in operation will be eligible to feature new signs alerting drivers where they can find these stations.[185]

In addition, California has unique authority under the Clean Air Act (CAA) to issue vehicle emission standards that are stricter than those issued by the Federal Government, and other states can adopt California's standards in their entirety. The California Air Resources Board adopted a zero-emission vehicle (ZEV) rule as part of the state's 1990 Low Emission Vehicle Program. Nine additional states have chosen to adopt California's ZEV rule to date: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. It is difficult to predict the future ZEV market penetration, but about 15.4 percent of new vehicles sold in participating states will be required to be ZEVs by 2025. By 2025, California needs to reach an estimated 265,000 ZEV sales per year—an increase of 250 percent over the next decade.[186]

Transit incentives are also available. For example, through the Low or No Emission Vehicle Deployment Program, the Federal Transit Administration provides funding to state and local governments for the purchase or lease of qualifying low- or no-emissions buses, including all-electric buses and related equipment and upgrades to facilities to accommodate new buses.[187] Qualifying airports can also seek Federal Government support for electrification of equipment and vehicles. The Federal Aviation Administration's Voluntary Airport Low Emissions and Zero Emission Vehicle Programs provide financial support for the purchase of electric equipment and vehicles.[188, 189]

3.2.5 Analytical Tools: Converting Data to Information Is Key to a Cleaner Electricity System

Real-time data at fine granularity and a suite of analytical tools and models will constitute the backbone of a modern, cleaner electricity system that integrates variable renewables and energy-saving technology. Other data and analysis tools will also be needed to inform decision making as governments, utilities, and consumers search for ways to maximize the benefits of new clean electricity technologies. There are several concerns related to the proliferation of real-time and other data. Of paramount importance are data privacy and security. Ensuring the completeness, quality, harmonization, and accessibility of data to decision makers is also very important.

Data needs and opportunities are particularly strong in electricity end-use consumption and energy efficiency. First, end-use surveys have gaps, such as a lack of water-sector data, and the end-use surveys have not kept up with shifting demand coming from the proliferation of new electronic appliances. Second, planners will need more granular data on energy consumption and energy efficiency to address grid operation needs due to new variable resources and increasing consumer energy management. Third, the increased ability to measure and monitor end-use data at finer scales brought by AMI and ICT provides an opportunity to target the specific energy efficiency measures most capable of reducing peak demand for a given location and season.

Updates to measurement and verification protocols, which vary by technology, can help drive the transition to a cleaner electricity system. The wealth of data being generated by AMI is enabling "evaluation, measurement, and verification 2.0" as discussed in Chapter II (*The Electricity System: Maximizing Economic Value and Consumer Equity)*.[cc] In California, some consumers now receive data on what type of generators are currently providing the electricity at their home or business. Based on the generation mix, the consumer can decide how much electricity to use in real time using a smart device. Established forms for DR, such as direct load control, have well understood and accepted methods for measuring the amount of DR available and deployed and for verifying that the intended and actual amount deployed are the same.[dd] Emerging forms of DR, such as aggregating reductions from residential critical peak pricing programs, are areas where continually improving measurement and verification will assist in the transition to a cleaner electricity system.

Improving data and analysis tools can help decision makers utilize energy efficiency measures for minimizing costs and ensuring reliability, including providing technical assistance on tools that enable the full consideration of energy efficiency as a resource. Analysis is needed at the appropriate level of granularity to inform understanding of system dynamics and behavior, including the effects of changing environmental conditions and resource availability, environmental impacts, and interactions between multiple infrastructures, such as electricity and water. For example, further analytical tools are needed at multiple spatial and temporal scales to better frame system-level tradeoffs related to resilience, economics, environmental impacts, and other factors that can inform design and policy decisions, such as those related to the integration of electricity and water systems.

For both national policy formulation and state integrated resource planning, there is often a need to make a determination on the level of savings that is cost effective from energy efficiency and other DERs (i.e., DR and DG). Currently, there is an incomplete patchwork of different energy efficiency potential studies (as well as studies that analyze the possible savings for other distributed resources) at the utility or state level that use a variety of different methodologies. These studies, which typically consider only energy efficiency, do not take into account the opportunity to integrate energy efficiency investments with other consumer options, such as DR, DG, and onsite storage—technologies to which consumers have growing access. A national demand-side resources potential assessment with sufficient geographical resolution could be used to more effectively integrate DERs into state and national energy policy. Due to the increasing availability of multiple demand-side resources, any potential assessment that considers only one of these resources will overestimate the savings from one approach while underestimating the impacts of an integrated approach. For example, a customer considering energy efficiency investments will have a different bill savings if they are already participating in a utility DR program for a given end use, like water heating or air conditioning.

In addition, enhancements to existing electricity-sector models will be required as climate change and other challenges affect the electricity system. The history of computer models in the electricity sector is extensive. The sector is highly dependent on modeling for planning, investment, regulation, and system

[cc] Updates to measurement and verification protocols, which vary by technology, can help drive the transition to a cleaner electricity system. The wealth of data being generated by AMI, along with improved analytical tools, are enabling advanced evaluation, measurement, and verification methods commonly referred to as "EM&V 2.0." see L. Schwartz, et al., *Electricity End Use, Energy Efficiency, and Distributed Energy Resources Baseline* (Lawrence Berkeley National Laboratory, January 2017), p 25-60; 310-311; 320-329.

[dd] A separate issue is verifying that the amount of DR that a utility or third party commits to provide is actually provided when called upon.

operations. Energy efficiency supply curves are not commonly used in electricity sector modeling because there are not sufficiently robust and granular (location- and technology-specific) data on the potential of energy efficiency measures for the entire Nation—something a national potential assessment could provide. For example, capacity expansion models, such as the National Energy Modeling System (NEMS), are widely used for policy formulation and resource planning. NEMS would particularly benefit from improvements in characterizing electricity end use, energy efficiency, DG, and storage.

Finally, enhanced models examining environmental impacts, resource base, and competing uses would be valuable in informing siting, permitting, and operational practices for generation. It would be useful for hydropower project models to illuminate environmental and land-use impacts and co-benefits. For geothermal energy, it would be valuable to characterize a substantial portion of the geothermal resource base, which could help to reduce siting and prospecting costs.[190] For CCUS projects, models can improve standardized site characterization that informs the determination of areas with the appropriate storage geology.

3.2.6 Electricity-System Assets, Operations, and Planning

There are many technical, market, and policy challenges related to how electricity-sector investment decisions and operations, Federal and state policy and regulations, and system and policy planning interact with efforts to shift to a low-carbon electricity system. To realize a cleaner electricity system, stakeholders will need to consider all aspects and integration of an end-to-end supply chain, from generation to end use.

Electricity infrastructure owners' choices on resilience, expansion, and modernization will have implications for achieving the nation's environmental goals, and vice versa. Chapter IV (*Ensuring Grid Reliability, Security, and Resilience*) discusses the need for and interaction between improvements in the electricity system's clean, resilient, and flexible characteristics. The same chapter adds that probabilistic planning is a robust method of assessing what infrastructure, including renewable generation, should be built for reliability purposes.

Integrating Energy and Capacity Markets with Clean Policies

In the summer of 2016, the New England Power Pool (NEPOOL) began a stakeholder process designed to explore whether the various environmental policies across member states could be integrated into the regional energy and capacity markets operated by Independent System Operator New England. Known as the Integrating Markets and Public Policy initiative, it has the potential to set an important precedent for how clean policies can be integrated into existing regional markets.

"Our goal at NEPOOL and for the region is to create a competitive market signal to get the states what they need so they don't have to act on their own. If we're successful, the markets on their own will find the most cost-effective means in meeting those state objectives." – NEPOOL Chairman Joel S. Gordon[191]

Following the release of an initial problem statement and guidelines in May 2016, stakeholders were invited to propose ideas at the group's first meeting in August. Proposals offered a wide range of solutions: from a carbon price adder, to a separate "clean-only" auction process called a "Forward Clean Energy Market," to strengthening the Regional Greenhouse Gas Initiative. Some proposals recommended price adjustments in the energy markets, while others offered modifications to the capacity markets.

Grid architecture alternatives are also important to consider for reaching a clean electricity future. Chapter IV (*Ensuring Grid Reliability, Security, and Resilience*) discusses architectural and operational alternatives to increase resilience. All of those alternatives, which decrease system response times and increase flexibility, would have important co-benefits in integrating renewable generation.

Efforts to improve near-term forecasting and granular grid visualization are already underway and have clear benefits for clean generation as are efforts to enhance situational awareness, and operational visibility for reliability, security, and resilience reasons. All of these methods would also lower the economic cost of renewable integration and are discussed in detail in Chapter IV (*Ensuring Grid Reliability, Security, and Resilience*).

Power market dynamics also affect clean power goals, and vice versa. Lower energy prices, which are partly due to low-cost natural gas and incentivized zero-marginal-cost resources, are reducing the economic viability of other desired clean resources, including nuclear energy.

Many of the planning-related challenges jurisdictional authorities face arise from the recent trend in technology advancement—and, specifically, the increase in new technologies and mechanisms focused at the end-use sector—behind the meter. This trend has caused a shift in the underlying assumptions upon which most planning requirements were established. There are many areas where Federal policy could facilitate the full consideration of the cost and benefits of energy efficiency, other demand-side management resources, and clean energy in planning processes, including improving data, advancing tools and representation in models, and providing technical assistance on tools that enable the full consideration of these clean resources in planning. The Federal Government is providing expanded technical assistance on methods of fully accounting for energy efficiency, other demand-side management resources, and clean energy in resource planning conducted by governments and utilities that could help break down institutional barriers to considering energy efficiency as a resource.

Other planning drivers exist as well. For example, evolving environmental requirements at the Federal level (e.g., the recently promulgated "Clean Power Plan" [CPP]) and clean energy goals at the state level (e.g., RPS) encourage jurisdictional authorities at the state level and across states to coordinate to ensure requirements are met at low cost.

As discussed in Chapter II. *The Electricity System: Maximizing Economic Value and Consumer Equity*, ratemaking[ee] is one of the public policy instruments that states use to incentivize and regulate the electricity sector. It is important that the environmental benefits of clean electricity are appropriately valued. To realize the full potential of increased DERs, clean energy generation, and more sophisticated grid technologies (such as smart meters and supervisory control and data acquisition systems), regulators "will need to utilize more advanced rate designs than they have in the past."[192] As DERs become more prevalent in the United States, for example, the traditional ratemaking models may no longer provide utilities with adequate means to properly recover the true costs of electricity generation, transmission, and distribution.[193] Public utility commissions have already begun to address this challenge in a wide variety of ways, reflecting states' different policy objectives and generation portfolios. Many states have instituted decoupling or lost-revenue adjustment mechanisms, which break the link between the amount of energy a utility sells and the revenue that it collects, increasing the utility's acceptance of energy efficiency programs. More recently, states have also begun to examine how to value the costs and benefits of DERs. Value of solar tariffs, for example, intend to "associate a quantifiable benefit with each kWh of distributed solar exported to the grid"[194] and translate this benefit into a dollar per kWh rate, giving utilities and regulators a pricing tool that reflects the value of this electricity better than retail or wholesale rates. As the role of clean energy in ratemaking continues to evolve, the Federal Government and states can cooperate to estimate the value attributed to electricity products and services, facilitate data and information exchange to guide ratemaking and rate design, and share lessons learned.

[ee] For a description of the rate design process, see Appendix A (Electricity System Overview).

3.3 Multiple Paths Forward for CO_2 Emissions Reductions from the Electricity System

As noted, the CO_2 intensity of the electricity system is expected to continue to decrease due to several factors, including fuel switching, technology innovation, and clean energy policies. The Federal Government has set economy-wide emissions reduction targets of 17 percent below the 2005 level by 2020, and 26 to 28 percent below the 2005 level by 2025.[195] These 2020 and 2025 targets were formally submitted to the United Nations Framework Convention on Climate Change in January 2010 and March 2015 respectively and they are consistent with a straight line emission reduction pathway from 2020 to economy-wide emission reductions of 80 percent or more by 2050.[196] An 80 percent economy-wide reduction in the United States, given commensurate reductions elsewhere, could help limit the increase in global mean surface temperature to 2 degrees Celsius and mitigate the worst impacts of climate change.[197] In order to achieve such deep levels of emissions reductions, it is likely that the electricity sector will need to provide greater and more immediate GHG emissions reductions than other sectors because it includes the most cost-effective options for reducing GHG emissions.

The President's "Climate Action Plan,"[198] the current U.S. strategy for addressing climate change, was formulated to mitigate global climate change and reduce U.S. GHG emissions. An example of a policy that, when implemented, will further the goals of the President's "Climate Action Plan" by continuing the trend of decreasing CO_2 intensity is the CPP, which was finalized by EPA in August 2015.[ff] Under Section 111(d) of the CAA, the CPP regulates carbon emissions from existing power plants and requires states to adopt plans to limit emissions from existing fossil fuel-fired power plants. EPA projects that, by 2030, the CPP will help cut carbon emissions from the power sector by 32 percent from 2005 levels.[199]

Tax credits for clean energy have also contributed to reduced CO_2 emissions and are projected to continue to help reduce electricity-sector emissions in the future.[200] NREL analysis projects a 50 GW increase in cumulative installed renewable energy capacity by 2020 due to the Federal tax credit extensions.[201]

3.3.1 A Record of Environmental Policy Successes

The successes of existing environmental policy are instructive for meeting future national environmental goals and objectives. The modern framework for improving air quality in the United States was established in 1970, with the creation of EPA and the passage of the 1970 CAA, which was subsequently amended in 1977 and 1990. While the electricity system has historically been a major source of air pollution, since the passage of the CAA, emissions of air pollutants (including sulfur dioxide and nitrogen oxides) have fallen dramatically below 1970 emissions levels. Between 1970 and 2014, aggregate emissions of common air pollutants from the electric power sector dropped 74 percent, even as electricity generation grew by 167 percent and the U.S. GDP grew 238 percent.[202, 203, 204]

The health benefits of reducing emissions of air pollutants from power plants and other sources include avoided premature deaths, avoided heart attacks, fewer cases of respiratory problems (such as acute bronchitis and asthma attacks), and avoided hospital admissions.[205, 206, 207] Air quality improvements from the Acid Rain Program, part of the CAA amendments of 1990, were estimated to yield health benefits of around $50 billion annually in 2010, compared to compliance costs that are on the order of $0.5 billion.[208, 209, 210, 211, 212] More recently, the 2012 Mercury and Air Toxics Standards, which established emissions limits

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[ff] On February 9, 2016, the Supreme Court stayed implementation of the CPP pending judicial review. The Court's decision was not on the merits of the rule. EPA firmly believes the CPP will be upheld when the merits are considered because the rule rests on strong scientific and legal foundations. EPA will continue to provide tools and support for the states that choose to continue to work to cut carbon pollution from power plants and seek the Agency's guidance and assistance.

for power plants for mercury, acid gases, and heavy metals, are projected to prevent up to 11,000 premature deaths, 4,700 heart attacks, and 130,000 asthma attacks every year.[213]

The economic benefits of clean air policies are also well-documented. A study looked at the impacts of the CAA amendments of 1990 and showed that—looking forward to 2020 in cumulative, net-present-value terms—there will be $2 trillion in benefits compared to $65 billion in costs, a benefit-cost ratio of over 30 to 1.[214] In addition, the United States is the world's largest producer and consumer of environmental technologies.[gg] In 2015, the U.S. environmental technologies and services industry employed 1.6 million people, had revenues of $320.4 billion, and exported $51.2 billion worth of goods and services.[215, 216] U.S. industry revenues for air pollution control alone totaled $19.6 billion, including equipment, instruments, and attendant services, while U.S. revenues for air quality monitoring instruments and information systems totaled $1.3 billion.[217] This experience shows that the United States has consistently been able to manage environmental pollution with benefits far outweighing the costs, all while continuing to grow the economy and support millions of jobs.

3.3.2 A Record of Clean Energy Technology Successes

The United States has historically been a global innovation leader, and the U.S. Government is one of the largest funders of electricity-sector RD&D in the world. The Federal Government's long standing electricity-sector RD&D investments, in concert with supporting policies, have made significant impacts on the Nation's electric infrastructure for decades through the present day.

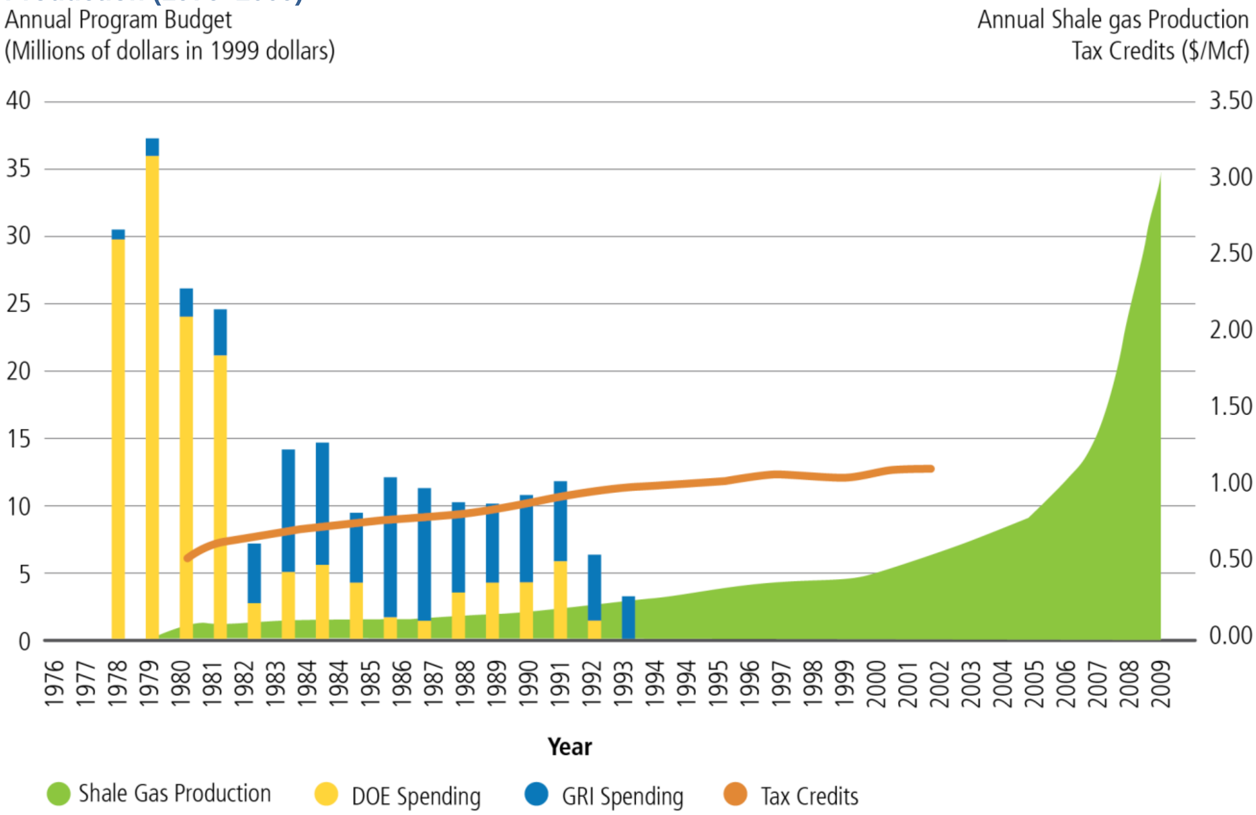
Shale Gas Research, Development, and Demonstration (RD&D) and Time-Limited Tax Credit

Early Federal shale gas RD&D funding, primarily for basin characterization and key drilling technologies, combined with a public-private partnership and a time-limited Federal Production Tax Credit, resulted in a sharp increase of shale gas in the mid-2000s (

[gg] Environmental technologies are devices that reduce the environmental impact of natural resources. Examples of environmental technologies that have contributed to the United States' success in reducing air pollution include activated carbon injection, flue-gas desulfurization, selective catalytic reduction, and dry-sorbent injection.

Figure 3-14). Today, shale gas is around 60 percent of total U.S. natural gas production. The interplay of early Department of Energy funding, industry-matched Gas Research Institute applied RD&D, and synergistic policy incentives enabled production from shales previously considered uneconomic. The switch from coal and petroleum power generation to less-carbon-intensive and more efficient combined-cycle natural gas generation resulted in over 1.2 billion metric tons of CO_2 emissions reductions from 2005 to 2014.[218]

Figure 3-14. Steady RD&D Funding and Time-Limited Tax Credit Led to Increase in U.S. Shale Gas Production (1976–2009).[219]

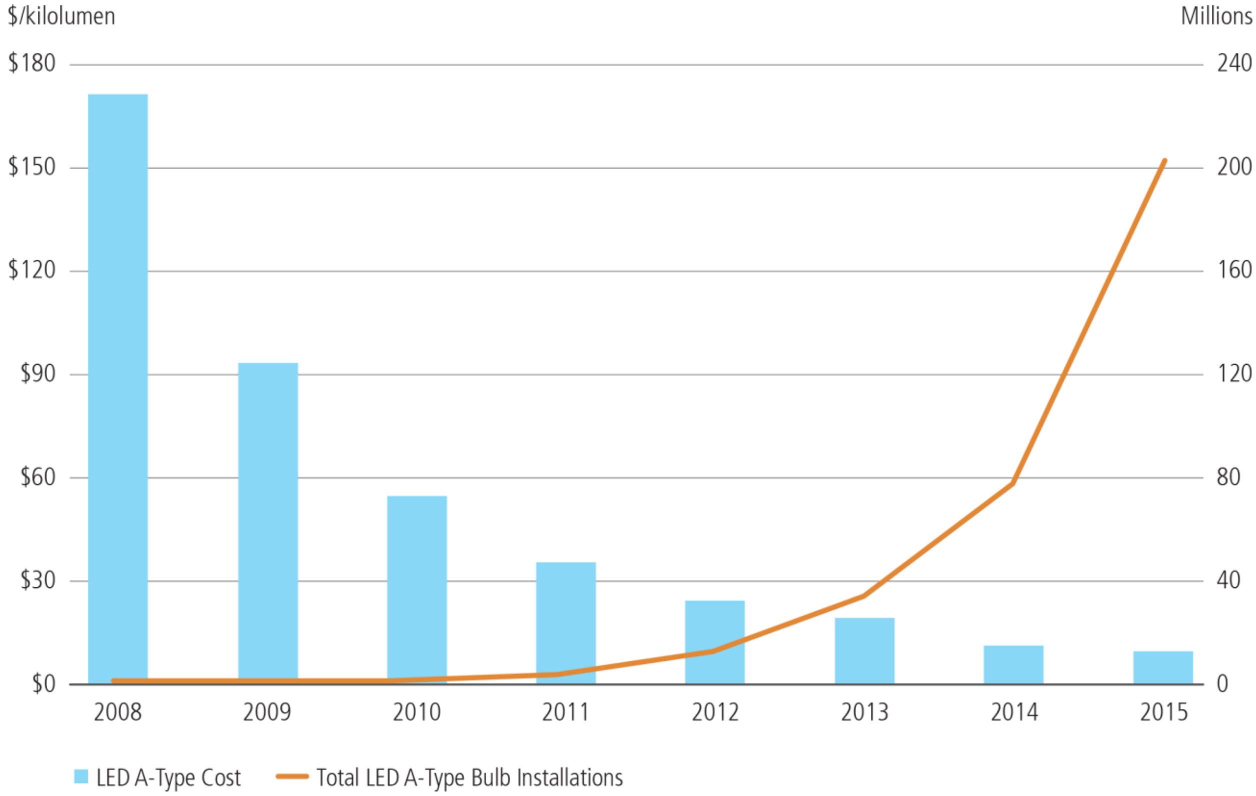


Federal funding, time-limited tax credits, and Gas Research Institute (GRI) funding led to a significant increase in gas production, starting in the mid-2000s.

Light-Emitting Diodes (LEDs) Research, Development, and Demonstration (RD&D) and Lighting Efficiency Standards

Federal and private-sector RD&D investments directly brought down LED costs, improved efficiency and performance, and fostered domestic manufacturing of LED lighting components and products.[220] Since the Department of Energy (DOE) began funding solid-state lighting research projects in 2000, large and small businesses, universities, and National Laboratories that received DOE funds have applied for more than 260 patents and developed more than 220 commercially available products in this technology area, including lighting products, power supplies, materials, and manufacturing tools.[221, 222] In 2007, Federal legislation set minimum operating life and energy efficiency standards for a majority of light sources used by the public, and relied heavily on technology innovation for manufacturers to meet those standards. The same legislation also mandated an efficient lighting competition, the "L Prize," that provided cash prizes and Federal Government purchase contracts for winning products. The combination of national lighting standards and lighting technology innovation investments and incentives has contributed to a rapid decline in LED product costs and a corresponding increase in LED sales (Figure 3-15).

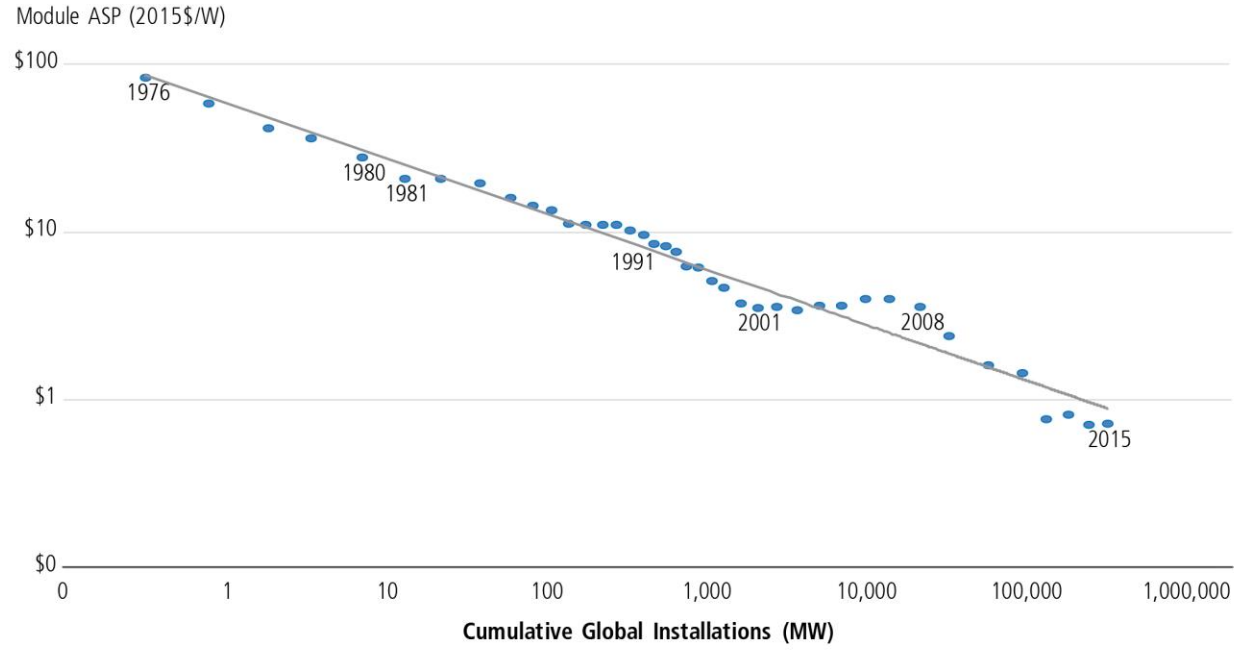
Figure 3-15. LED Costs and Installations, 2008–2015[223]



LED bulbs now account for 6 percent of all installed A-type bulbs, which are common in household applications. This growth has been enabled by a 94 percent reduction in cost since 2008. In 1 year, total installations of common home LED bulbs more than doubled from 77 million to 202 million—a particularly rapid growth considering there used to be fewer than 400,000 installations as recently as 2009. Across all LED product types, LED installations prevented 13.8 million metric tons of CO_2 emissions and saved $2.8 billion in energy costs in 2015 alone.

Solar PVs (Figure 3-16), LEDs, and shale gas development are among many other electricity-related technologies that demonstrate the instrumental role of Federal investment in early stage R&D. As technologies mature, these case studies also show the need for both innovation and policy, and illustrate the synergistic interactions among complementary innovation and policy efforts. For example, innovation investments reduce the cost of policies and incentives and allow decision makers in both government and the private sector to consider options that would otherwise not be available. Increased deployment levels due to policies and incentives also increase economies of scale and further reduce manufacturing costs and technical risks.

Figure 3-16. Long-Term Solar PV Cost Decline and Global Deployment Growth, 1976–2015[224, 225, 226, 227, 228]



This experience curve displays the relationship, in logarithmic form, between the average selling price (ASP) of a PV module and the cumulative global shipments of PV modules. Average module prices have dropped by about a factor of 100 since 1976 to under $1/watt (W), while cumulative module shipments have increased from less than 1 MW to over 200 GW. For every doubling of cumulative PV shipments, there is, on average, a corresponding reduction of about 20 percent in PV module price. Acronyms: watt-peak (Wp); megawatt-peak (MWp).

3.3.3 Market-Based Carbon Policies

A transparent, market-based policy to price carbon emissions has been documented as the most cost-effective way to reduce GHG emissions.[229] Market-based incentives such as a carbon charge or price encourage actors in the economy, including consumers and utilities, to internalize the costs to society of emitting GHGs. In addition, a transparent, market-based policy to price carbon emissions drives the most cost-effective emissions reductions first, which achieves the goal of reducing CO_2 emissions at the lowest cost. Long-term carbon pricing policies also reduce uncertainty and send clear market signals that encourage innovators to develop new and improved clean energy technologies.

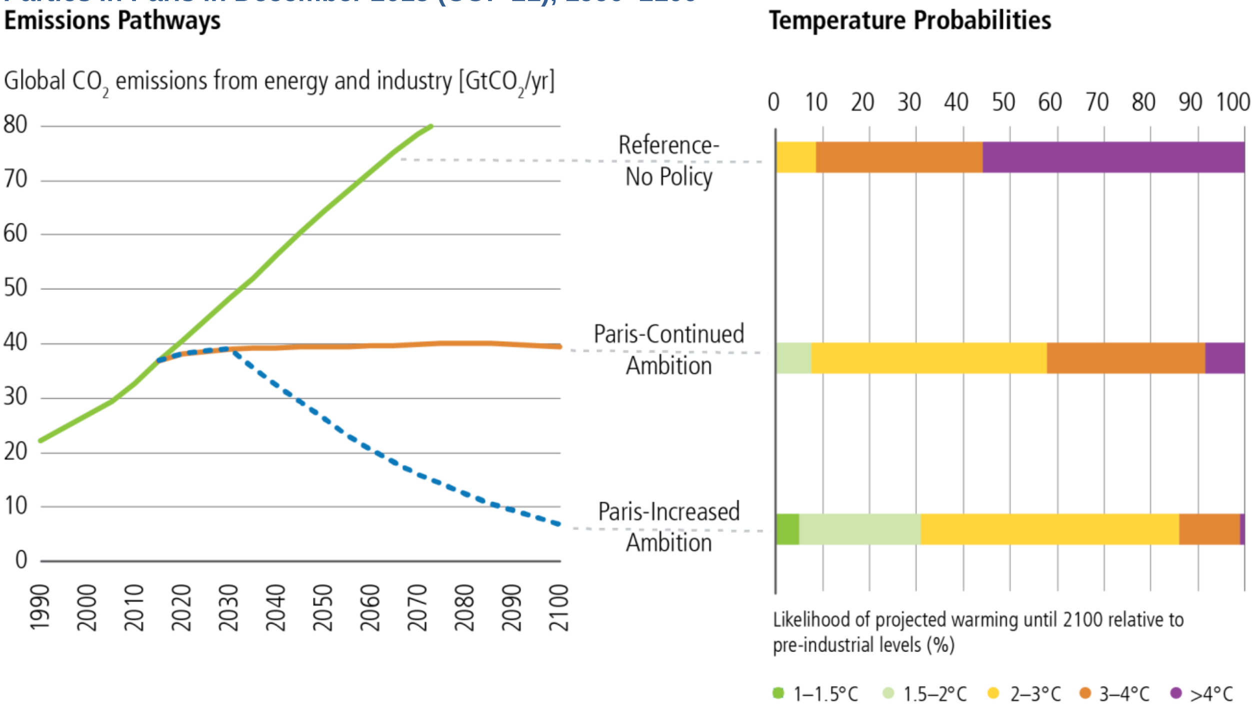
Ten U.S. states are currently implementing market-based carbon pricing policies. For example, nine states in the Northeast and Mid-Atlantic are implementing the Regional Greenhouse Gas Initiative, which is a multi-state GHG cap-and-trade program.[230] Investments spurred by the Regional Greenhouse Gas Initiative are estimated “to save 76.1 million Btu of fossil fuels and 20.6 million MWh of electricity” over the lifetime of these investments.[231] California is implementing Assembly Bill 32, the California Global Warming Solutions Act, which was enacted in 2006. Assembly Bill 32 requires the reduction of statewide GHG emissions to 1990 levels by 2020. One component of California’s program is a statewide GHG cap-and-trade program.[232] California’s program is linked to Quebec’s program, allowing for cross-border GHG emissions trading. Carbon emissions are falling faster than anticipated and the demand for emission allowances has been decreasing.[233, 234] Although the United States does have a Federal cap-and-trade program for sulfur dioxide emissions, there is no market-based policy for GHGs at the Federal level.[hh]

3.3.4 Addressing Climate Change, Growing the Economy through Innovation

Climate change is one of the world's major challenges. The 17 warmest years on record have occurred in the last 18 years.[235] 2015 was the warmest year on record, and based on the latest data, 2016 is expected to set a new record.[236, 237] Global temperatures have already warmed 0.85°C from preindustrial times.[238]

The successes of the CAA offer lessons about our ability to simultaneously address environmental concerns and grow the economy. Mitigating climate change is, however, intrinsically more complicated because it is a global problem that affects all sectors of the economy.

Figure 3-17. Global CO_2 emissions (*left*) and Probabilistic Temperature Outcomes (*right*) of United Nations Framework Convention on Climate Change's 21st session of the Conference of the Parties in Paris in December 2015 (COP 21), 1990–2100[239]



Implementing the 21st Conference of Parties pledges could significantly reduce the chances of a level of warming greater than 4 degrees Celsius by 2100 (as seen under the Paris-Continued Ambition scenario). However, to decrease the likelihood of projected warming above 2 degrees Celsius, additional actions are required (as seen under the Paris-Increased Ambition scenario).

The Paris Agreement, adopted in December 2015, explicitly acknowledged that climate change warranted a global response, with more than 190 countries agreeing to make national commitments to substantially reduce their GHG emissions.[240] In an effort to reduce the risks and effects of climate change, the Paris Agreement sets a goal to keep global average temperature rise to no more than 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius.[241] Reports issued by the Intergovernmental Panel on Climate Change suggest that in order to limit warming

[hh] The CPP provides states with flexibility to choose different pathways (some of which are market-based) to comply. If all states choose a market-based policy under the CPP a Federal market is not necessarily created.

to 2 degrees Celsius to mitigate the worst impacts of climate change, developed countries must achieve deep decarbonization by reducing their emissions by 80 to 95 percent relative to a 1990 baseline.[242, 243] Pursuant to the Paris Agreement, all countries must commit to submitting successive nationally determined contributions (NDCs) every 5 years that "represent a progression" beyond their current NDC and which outline what each country plans to do to address climate change.[244] The emissions under the current NDCs (the orange line in Figure 3-17) are too high to limit warming to 2 degrees Celsius. Additional actions to reduce emissions are needed.

The U.S. commitment in Paris affirmed that the United States is prepared to pursue further reductions beyond the previously announced "economy-wide target of reducing its GHG emissions by 26 percent to 28 percent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28 percent."[245] The United States formally joined the Paris Agreement on September 3, 2016,[246] and is strongly committed to taking action and global leadership to address climate change.[247]

Projecting out to the mid-century and beyond, the literature suggests that the rate of emissions reductions will need to significantly speed up to stay on track to meet the 2 degrees Celsius warming target and reduce the risk of the most severe projected impacts of climate change.[248]

3.3.5 Realizing Future GHG Reductions: DOE Integrated Modeling Assessment

A disparate set of technologies and Federal and state policies are in place that have reduced and can further reduce emissions from the power sector. An integrated assessment of the roles these varying solutions might play as they compete with and/or complement one another can further inform both policy and technology pathways to achieve the deep decarbonization needed to meet the goals established by more than 190 countries in Paris.

Consumers make their own decisions about how much electricity to use based on their needs as well as electricity prices. The projections described below will provide insight about what could happen to GHG emissions in the future and help inform power companies, regulators, policymakers, and consumers as they make decisions about electricity supply, the performance and cost of technology options, and the appropriate regulatory, market, investment, and incentive structures.

To explore how the electric power sector can contribute to U.S. efforts to address climate change, DOE constructed several illustrative scenarios as part of the analysis conducted for the QER. The scenarios presented here are not intended to be forecasts. Rather, they reveal possible implications for electricity supply, demand, and GHG emissions for a reasonable range of economic and technology assumptions. This analysis used EPSA-NEMS,[ii] an integrated energy system model, to explore how electricity demand may evolve and also the potential future composition of the electric power sector, both from the perspective of electricity generation and installed capacity. A summary of the analysis cases is found in Table 3-3.

[ii] The version of NEMS used for the EPSA Base Case has been run by OnLocation, Inc., with input assumptions determined by DOE's EPSA. This analysis was commissioned by EPSA and uses a version of NEMS that differs from the one used by the Energy Information Administration. The model is referred to as EPSA-NEMS.

Table 0-3. Summary of DOE QER Analysis Cases using EPSA-NEMS[249, 250]

Case	Description
Base Case	Based on the "Annual Energy Outlook 2015" High Oil and Gas Resource Case, with (1) updated cost and performance estimates for CCUS, solar, and wind, and (2) adjustments to incorporate all existing U.S. policies that were final at the time of this analysis, the most recent of which were the CPP and the December 2015 extension of the Federal Renewable PTC and ITC.[jj]
CCUS Incentives Analysis	A variation of the Base Case where the DOE RDD&D program goals for CCUS technologies are achieved. Two potential CCUS incentives are considered: • CCUS incentives in the Administration's fiscal year 2017 budget proposal, including a refundable sequestration tax credit of \$10/metric ton CO_2 for EOR storage and \$50/metric ton CO_2 for saline storage, and a refundable 30 percent ITC for carbon capture and storage equipment and infrastructure • A hypothetical revision of the Section 45Q sequestration tax credits[kk] to provide a credit of \$35/metric ton CO_2 for EOR storage and \$50/metric ton CO_2 for saline storage.
Advanced Technology	Current DOE energy program goals (including cost, performance, and deployment goals) overlaid on top of the Base Case.
Stretch Technology	More ambitious RDD&D program goals (including cost and performance goals) overlaid on top of the Advanced Technology Case, based on an assumption of additional RDD&D, such as what could be enabled by Mission Innovation (which will be discussed in Section 3.3.7).
Carbon Price (CP 10)	As a proxy for additional policy action, an initial carbon price of \$10/metric ton of CO_2, starting in 2017 and rising at 5 percent per year in real dollars, was overlaid on top of the Base Case, Advanced Technology Case, and Stretch Technology Case.
Side Cases	The Base, Advanced Technology, and Carbon Price (CP 10) Cases were also modeled using the "Annual Energy Outlook 2015" Reference case assumptions instead of the High Oil and Gas Resource assumptions—the "Annual Energy Outlook" Reference case has lower resources (higher natural gas and oil prices). All other inputs explained above stayed the same.

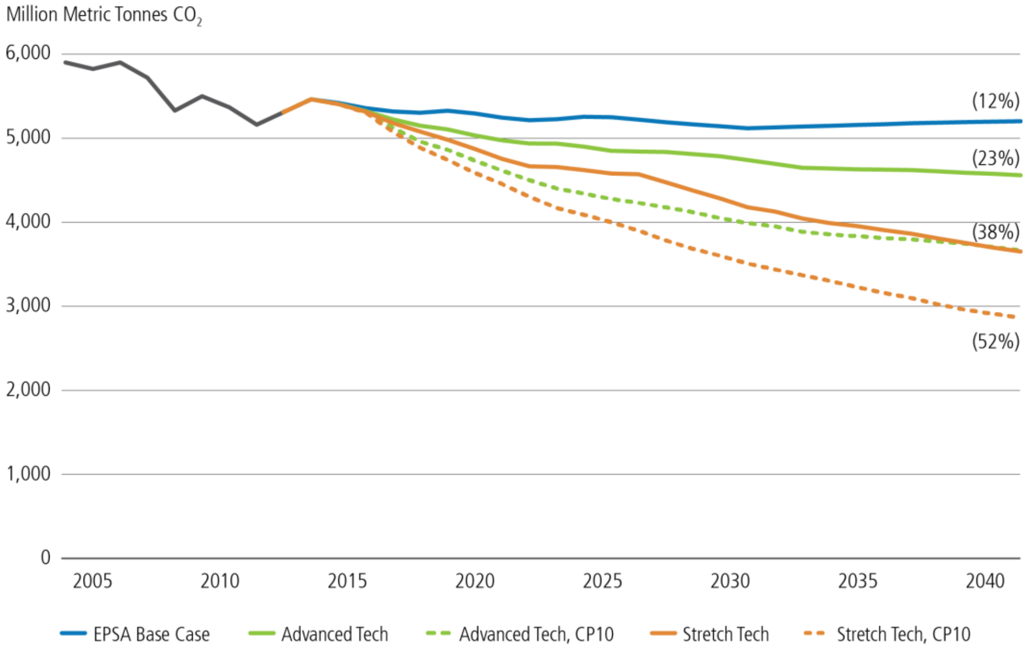
Table 3-3 summarizes the technology and policy assumptions underlying several illustrative analysis cases that DOE constructed to explore how the electric power sector can contribute to U.S. mitigation efforts for climate change.

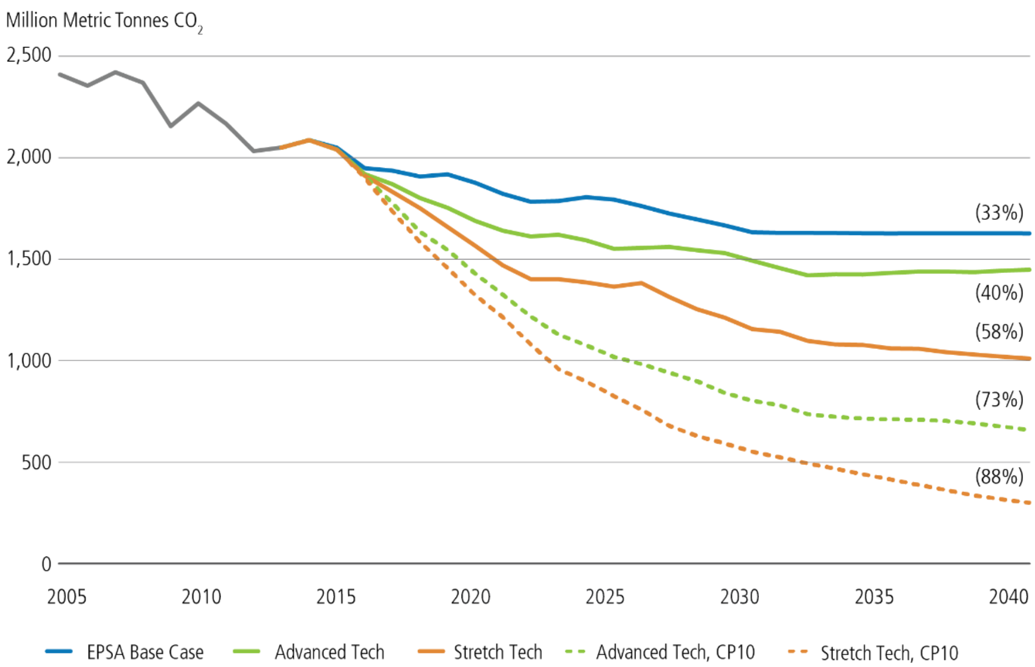
The resulting range in the projected electricity generation mix for a selected set of cases is shown in Table 3-4. These projections reflect only one possible future for the generation mix. The full range of technologies that could be deployed in a future generation portfolio is still unknown. However, both the Advanced Technology and Stretch Technology Cases see an increase in the market share of many low- and zero-carbon generation sources, particularly when additional policies, such as a carbon price, are applied (Figure 3-18).

[jj] The Consolidated Appropriations Act of 2016, signed into law in December 2015, extended the Federal PTC for wind facilities that commence construction before 2020, although the value of the PTC will be phased down for wind projects commencing construction after December 31, 2016. The PTC for all other technologies expired at the end of 2016. The Consolidated Appropriations Act of 2016 also extended the full Federal ITC for solar facilities that commence construction before 2020, after which the value of the ITC will be phased down to 10 percent in 2022 and all years thereafter. The full ITC was also available for large wind facilities through 2016, after which the value was phased down for projects commencing construction before December 31, 2019. The ITC for all other technologies expired at the end of 2016, with the exception of geothermal electric facilities, which receive a 10 percent ITC indefinitely.

[kk] 26 U.S.C. § 45Q provides a credit for CO_2 sequestration.

Figure 3-18. U.S. Energy CO_2 Emissions, 2005–2040 (*top*), and U.S. Electricity-Sector CO_2 Emissions, 2005–2040 (*bottom*)[251]





Top: Projections of energy CO_2 emissions are shown for several cases along with the corresponding percent decrease in CO_2 emissions relative to a 2005 baseline. These results indicate that successful clean energy RDD&D can drive significant emissions reductions beyond those projected under the EPSA Base Case (which incorporates all existing policies but assumes no new policies). Current levels of RDD&D investment in clean energy technologies (Advanced Technology) can double the projected emissions reductions by 2040, while more ambitious advancements in clean energy technologies (Stretch Technology) could triple the emissions reductions by 2040. These results also indicate that a combination of policy "pull" and technology "push" can achieve much greater reductions than policy or technology alone.

Additional technology and/or policies beyond what was modeled are needed to obtain energy CO_2 emissions reductions that are consistent with goals of deep decarbonization.

Bottom: Projections of CO_2 emissions associated with electricity generation are shown for several cases. The sharp reductions projected in the near future can be largely attributed to a cleaner electricity generation mix as more high-carbon generation is offset by a variety of low- and zero-carbon generation sources. Reductions in electricity demand, primarily from more efficient building shells and equipment, and faster adoption at lower cost of more efficient building technologies, also play a major role in driving down electricity-sector CO_2 emissions throughout the analysis. Altogether, these analysis cases show that successful, clean energy RDD&D can drive emissions reductions beyond what is achieved with current policies, measures, and projections for technology advances. In addition, there are multiple pathways to achieving even greater reductions in CO_2 emissions associated with electricity generation through additional technology and/or policies.

DOE performed an analysis to explore the impact of RDD&D and tax incentives on the deployment of CCUS technologies (Table 0-3).[252] The analysis considered tax incentives proposed in the Administration's fiscal year 2017 budget, as well as a hypothetical revision of the Section 45Q sequestration tax credits. The analysis found that Federal RDD&D combined with tax incentives can make CCUS a viable option, and that CCUS can play an important role in meeting a carbon policy. DOE's analysis found that CCUS incentives and RDD&D could result in significant deployment of CCUS generating capacity. Under the scenario combining tax incentives with successful RDD&D ("CCUS Incentives Analysis"), coal and natural gas generating capacity with CCUS accounted for an incremental 5 to 7 percent of total generation in 2040 (Table 0-4). For comparison, in 2015, hydropower accounted for 6 percent of total generation, and all other renewables totaled 7 percent of total generation.

Table 0-4. Percent of Utility-Scale Generation by Fuel Source, 2015, and Projected to 2040 for Selected Cases[253, 254]

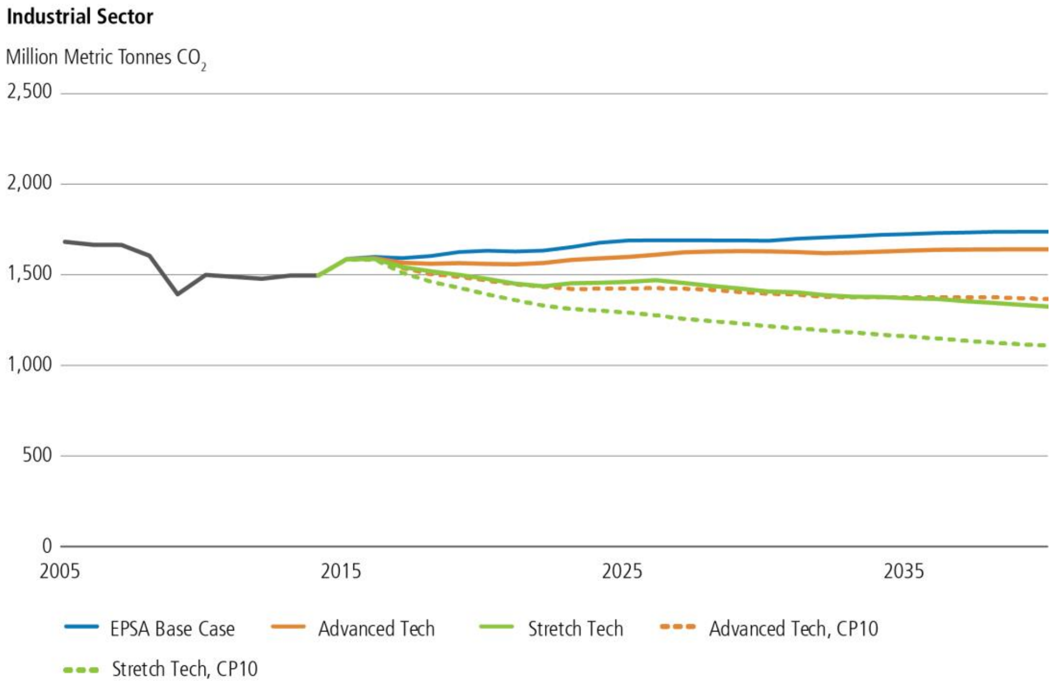
	2015	2040			
Fuel Type	**Base Case**	**Base Case**	**Advanced Technology**	**Carbon Price (CP 10)**	**CCUS Incentives Analysis**
Coal without CCUS	39%	18%–28%	23%–31%	4%–14%	19%
Coal with CCUS	0%	<1%	<1%	<1%	3%–4%[a]
Natural Gas without CCUS	27%	21%–42%	11%–28%	13%–31%	37%–38%
Natural Gas with CCUS	0%	0%	0%	1%–2%	2%–3%[a]
Conventional Hydropower	7%	6%–7%	7%	7%–8%	6%
Non-Hydro Renewables	7%	17%–25%	26%–30%	36%–38%	14%
Nuclear Power	20%	17%–19%	15%–20%	21%–28%	17%

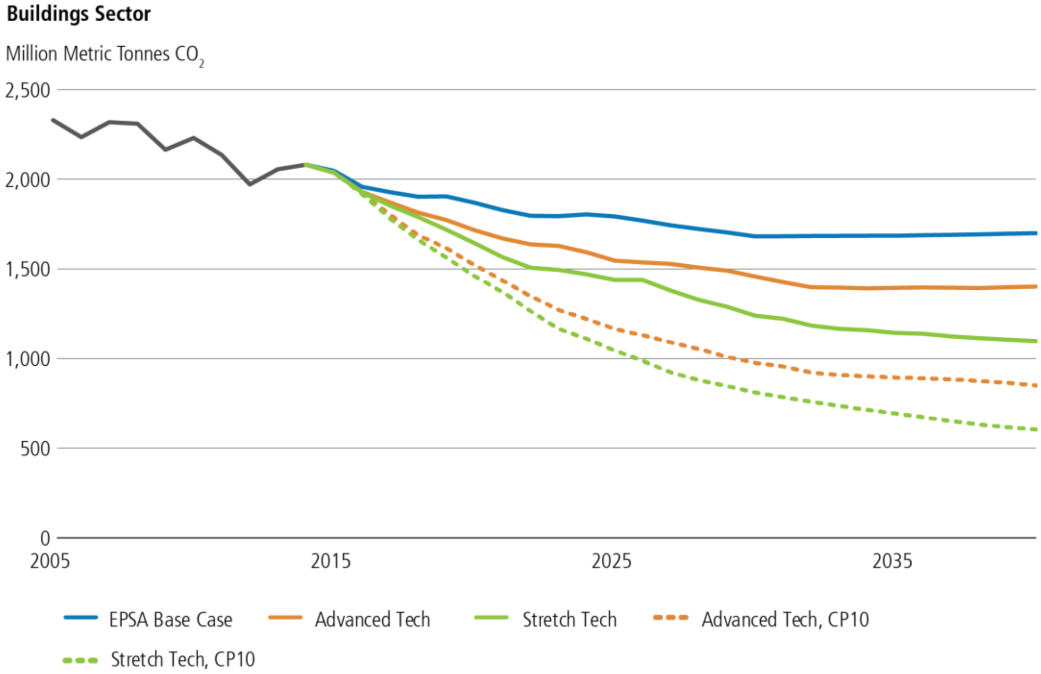
[a] Incremental to generation without CCUS.

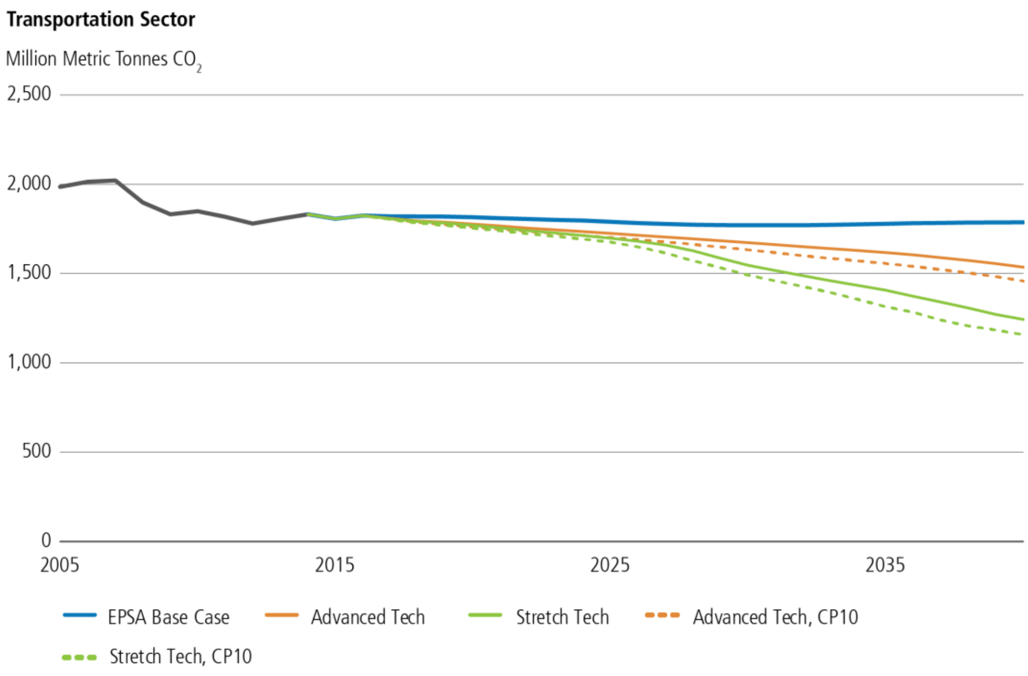
The range in percentages shown in 2040 in the Base Case and Advanced Technology Case highlights the significant impact that future natural gas prices will have on the modeled U.S. electric power generation mix. Similarly, the incentives included in the CCUS Incentives Analysis illustrate the potential to increase penetration of CCUS technologies with additional incentives.

A significant investment in clean energy RDD&D, coupled with an economy-wide policy, would accelerate innovation and technology deployment and reduce CO_2 emissions from the power sector by 88 percent in 2040, relative to 2005 levels.[255] The level of emissions reductions in the Stretch Technology scenario reflects a portfolio approach to RDD&D and is only illustrative, as technology pathways are highly uncertain; unforeseen research breakthroughs are very difficult to anticipate in modeling analysis; and generation breakouts are too uncertain to present here. This uncertainty, coupled with the value of RDD&D in meeting deep emissions reductions, underscores the need for a broad, diverse, and robust research portfolio. Another large source of emissions reductions in the DOE analysis is electricity demand reductions, which can be achieved by technology cost and performance improvements that increase electricity end-use efficiency, and pairing these improvements with a modest carbon price. The modeling analysis suggests that, with these investments and supportive policies, electricity demand would increase by only 5 percent over the next 25 years compared to 21 percent without them.

Figure 3-19. Total Direct and Indirect CO_2 Emissions by End-Use Sector, 2005–2040[256]



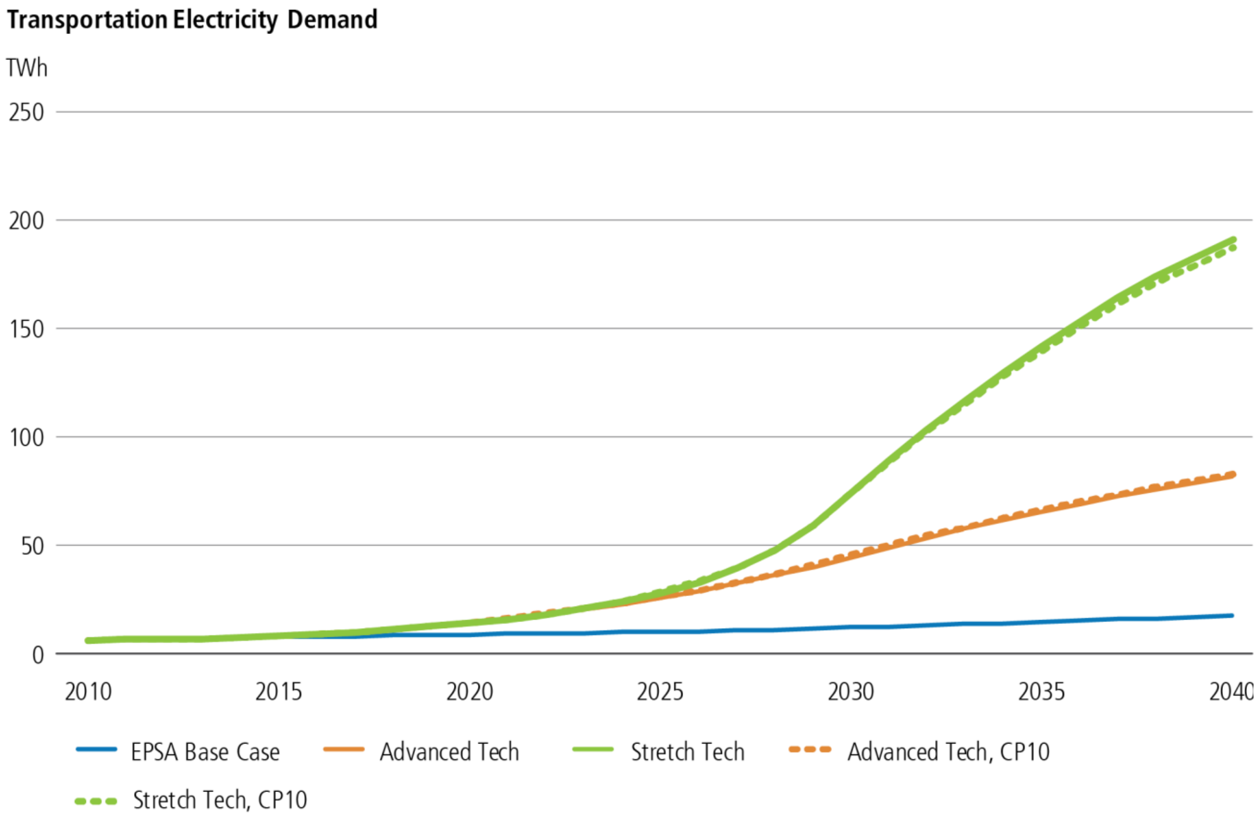




This figure shows the projected impact of technology and policy assumptions on total CO_2 emissions from the industrial (*top*), buildings (*middle*), and transportation (*bottom*) sectors, including emissions associated with both (1) direct fuel use (direct emissions) and (2) electricity generation allocated to end-use sectors based on their electricity use (indirect emissions). Successful clean energy RDD&D is projected to reduce end-use CO2 emissions by accelerating the transition towards a cleaner electricity generation mix and the adoption of cleaner and more efficient technologies. Both efficiency improvements (especially in energy-intensive industries) and additional policy can drive significant emissions reductions in industry and buildings. Technology advances can have a significant impact in the transportation sector, but the modest carbon price proxy does not dramatically reduce transportation emissions.

In the Stretch Technology Case, even greater investment in successful clean energy RDD&D is projected to result in more significant efficiency improvements, and electricity demand is projected to actually *decrease* by approximately 1 percent over the next 25 years. In both the Advanced Technology and Stretch Technology Cases, there is a decrease in electricity demand in both the industrial and buildings sectors, primarily due to technology improvements that result in increased efficiency (Figure 3-19). Conversely, in the transportation sector, electricity demand increases as the market starts to adopt more battery electric vehicles; however, electricity use in the transportation sector is still very small compared to other sectors. In 2040, transportation only accounts for 2 percent of electricity demand in the Advanced Technology Case and 6 percent in the Stretch Technology Case (Figure 3-20).

Figure 3-20. Electricity Demand by the Transportation Sector, 2005–2040[257]



The DOE scenarios all project a small but growing shift towards electrification in the transportation sector. In the Advanced Technology and Stretch Technology Cases, advances in RDD&D lead to increased market penetration of alternative vehicles, including battery electric and fuel cell light-duty vehicles. In 2040, battery electric vehicles and hydrogen fuel cell vehicles comprise 18 percent of new light-duty vehicle sales in the Advanced Technology Case and 40 percent of new light-duty vehicle sales in the Stretch Technology Case.

The potential for emissions reductions by specific end-use sectors was also analyzed. Total CO_2 emissions account for both (1) the CO_2 emissions associated with each sector's electricity generation and (2) emissions from direct fuel use (e.g., industrial process emissions and vehicle tailpipe emissions).[ll]

[ll] Emissions from end-use sectors are typically referred to as indirect emissions (emissions associated with the generation of electricity used by each sector) and direct emissions (direct fuel-use emissions).

Technology advances and/or additional policy are projected to drive dramatic emissions reductions from the buildings sector due to a cleaner electricity generation mix and reduced electricity demand through more efficient building shells and equipment, as well as faster adoption at lower cost of more efficient technologies. Similarly, successful clean energy RDD&D and/or additional policy drive reductions in industrial-sector CO_2 emissions through efficiency improvements (especially in energy-intensive industries); additional policy is also projected to have a significant impact. Finally, in the transportation sector, where use of electricity is currently very limited, opportunities exist for significant emissions reductions through efficiency improvements and the successful deployment of electric and hydrogen fuel cell vehicles, but the application of a modest carbon price has only a minor additional impact on transportation emissions.

In addition to showing the value of synergistic research investments and policy, the analysis shows that the electricity sector is most sensitive to a carbon price policy, partly because it already has a variety of relatively low-cost substitution options available. Finally, this analysis supports the finding that as the electric grid becomes increasingly decarbonized, electrification of end uses can result in further reductions of energy CO_2 emissions.

3.3.6 Need for Accelerated Electricity System

Even with notable increases in clean technology deployment in recent years, the scale-up and speed of clean energy technology[mm] innovation for the electricity system need to accelerate. As noted, increasing RDD&D in conjunction with an economy-wide policy can help the United States meet its NDC. There are also multiple direct and indirect benefits of electricity-sector technology innovation investments. Innovation investments directly expand the pipeline of new technologies, reduce technology costs, and mitigate the risks of new technologies or systems. These benefits, in turn, reduce the cost of policies and incentives[258] and allow decision makers in both government and the private sector to consider options that would otherwise not be available. Increased deployment levels due to policies and incentives also increase economies of scale and further reduce manufacturing costs and technical risks. In addition, innovation investments can serve to train the next generation of scientists, engineers, and entrepreneurs for work in the private sector or at universities or other research institutions.[259]

However, comparisons with other innovation-driven sectors and other countries, declining private-sector energy innovation funding, and increasing needs for electricity-sector innovation all point to an inadequate level of current support in the United States.[260, 261, 262, 263, 264, 265, 266] For example, annual global corporate and venture capital investment in renewable energy innovation grew from $3.6 billion in 2004 to a peak of $7.6 billion in 2011, but this investment has since fallen to $5.5–$6.0 billion in 2014–2015. Annual global venture capital and private equity investments in early-stage renewable energy firms have fallen even more drastically, from a peak of $9.9 billion in 2008 to $2.1–$3.4 billion in 2013–2015.[267] In the United States, similar trends show that annual venture capital investments in clean energy technologies fell from a 2008 peak of over $5 billion to about $2 billion each year since 2013. From 2006 to 2011, only 5 percent of early-stage clean energy technology firms returned profits to their investors through acquisition or an initial public offering, as opposed to 18 percent of early-stage software firms started during the same period.[268] Private-sector energy firms also spend significantly less on R&D as a percentage of sales than firms in other major technology-dependent sectors, such as pharmaceuticals, aerospace and defense, and computers and electronics.[269] Private-sector investment, while critical, will

[mm] Clean energy technologies are defined as energy-related hardware, software, and systems that avoid, reduce, or sequester GHG emissions or other air pollutants, including technologies that convert, convey, or store energy resources; improve energy efficiency; or reduce energy consumption.

not likely be made at a pace sufficient to meet national objectives.[270, 271, 272, 273] Electricity-sector technology innovation is subject to many barriers. For example, prices do not reflect external benefits[nn] of clean energy; investments are made in a highly regulated environment; and there are high capital costs and long-time horizons for RD&D and capital stock turnover in comparison to other sectors, such as information technology. Current levels of Federal support for electricity-sector and other energy-focused RD&D need to be substantially increased.[274, 275, 276, 277, 278, 279, 280, 281, 282, 283] Regional variation in innovation capabilities, infrastructure, markets, policies, and resources also points to a need to address electricity-sector innovation through regional approaches.[284]

The Advanced Research Projects Agency–Energy (ARPA-E) Program and Electricity Innovation

The Department of Energy's ARPA-E funds technically innovative, high-risk, high-potential energy projects that are too early for private-sector investment but could significantly advance how the Nation generates, stores, distributes, and uses energy.[285] ARPA-E competitively supports innovative ideas with the specific purpose of advancing them from early-stage concept to application prototype. One of the Mission Innovation goals that ARPA-E supports is to deliver more investment-ready, innovative energy technologies for private-sector investors and industry to commercialize. To date, 45 ARPA-E projects have attracted more than $1.25 billion in private-sector follow-on funding to support commercial development.

There is significant opportunity for accelerating the development of more innovative project concepts based on the number of applications for ARPA-E projects. On average, ARPA-E is only able to fund 10 percent of the proposals for its focused solicitations, and only 1.4 percent of the proposals that it receives in its open solicitations.[286]

Many of ARPA-E's programs are directly or indirectly focused on breakthroughs for the electricity sector. For example, the Green Electricity Network Integration program has supported the development and demonstration of new grid optimization technologies such as power flow controllers.[287] By redirecting power away from congested lines, power flow controllers can increase transmission capacity without construction of new assets.[288]

The spectrum from early- to late-stage energy innovation spans a highly interactive process that includes invention, translation, adoption, and diffusion. These four stages, which continually influence each other, roughly correlate to the classic linear innovation categories RDD&D.[289] Challenges to accelerating electricity-sector technology innovation vary widely between technologies and innovation stages.

For example, some electricity-sector technologies, such as nuclear, CCUS, and offshore wind, have capital costs that are a relatively high share of total costs in comparison with other technologies. High capital cost projects typically require first-of-a-kind demonstrations at commercial scale where system engineering challenges and large infrastructure costs predominate. Commercial-scale demonstrations often take tens or hundreds of millions of dollars to execute and may carry high technical and market risk.[290] These challenges can simply be too large for a single firm to take on, and the time to provide a return for private investors is often longer than investors can wait.[291]

Although there is substantial research on the value and impact of energy technology innovation, particularly for individual technologies, there are few robust measures and quantitative assessments of the energy innovation system, particularly of private-sector inputs, as well as meaningful outputs and impact measures. Refined, data-driven frameworks and models on energy innovation, including policy

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[nn] R&D is a classic example of an activity that has positive externalities for society. Externalities represent a difference between private and social gains. R&D has positive effects beyond those enjoyed by the producer that paid for the R&D because R&D expands general knowledge, and in turn, enables other discoveries and developments. A private firm only receives benefits from its own products; generally, the private actor does not capture the profits from others who benefited indirectly. With all positive externalities, private returns are smaller than social returns.

interactions, are needed to understand better how inputs and outputs of energy innovation systems relate to each other.[292, 293, 294, 295, 296]

Electricity-sector technology areas that received substantial investment increases in the fiscal year 2017 President's budget include energy storage; grid modernization; energy-water nexus; subsurface science, technology and engineering; CCUS; and renewable generation technologies such as solar, wind, water, and geothermal. Promising breakthrough technology areas include improving flexible power delivery and communications; developing non-vapor compression systems that provide highly energy efficient space conditioning, water heating, and refrigeration services in buildings without the use of traditional refrigerants; producing low-cost hydrogen from renewable or low-carbon sources; scaling up novel CO_2-capture technologies from power plants and industrial sources; and recycling CO_2 into valuable products as a feedstock.

3.3.7 Mission Innovation: Accelerating Clean Electricity Technology RDD&D

In November 2015, the United States and 19 other nations came together to make a landmark commitment—called Mission Innovation—to dramatically accelerate global clean energy innovation. This charter group of Mission Innovation countries, as well as others that have joined since, are seeking to double their public investment in clean energy R&D over 5 years. Accordingly, Mission Innovation will result in nearly $30 billion of public investment in 2021.

The Enabling Framework for Mission Innovation outlines examples of proven and powerful approaches to RD&D that will be critical elements of the U.S. domestic implementation of Mission Innovation.[297] Robust implementation must incorporate multiple linear and nonlinear approaches, not just in terms of technologies, but also in terms of technology pathways. This means funding programs that leverage foundational mechanisms to increase breadth of knowledge within a scientific discipline; translational mechanisms to target incremental improvements along defined tech-roadmaps; disruptive mechanisms to validate high-risk, high-reward off-roadmap ideas; and integrational mechanisms to facilitate collaboration across disciplines and stakeholders.

The Framework uses five specific areas of focus to illuminate these opportunities, all of which are either specifically or partly related to electricity: generation (i.e., harnessing electricity from clean sources); mobility (i.e., moving people and goods using clean energy); connections (i.e., delivering clean energy from supply to demand); structures (i.e., innovating better buildings); and processes (i.e., using clean energy to create products and grow food). As outlined in the Domestic Implementation Framework,[298] the domestic implementation of Mission Innovation could

- "*Drive down energy costs:* Clean energy technologies have the potential to dramatically reduce long-term energy expenditures.[299] This could increase the competitiveness of U.S. businesses and put thousands of dollars in the pocketbooks of American families.
- *Enhance system reliability:* Energy services are deeply embedded into all critical infrastructures and services, including the electric grid, transportation, and telecommunications. Advanced energy technology can improve system reliability.
- *Improve energy security:* Using more diverse energy sources and technologies can increase the resilience and flexibility of the domestic energy supply chain, helping to protect energy consumers from high-cost market disruptions and reducing exposure to markets with high price volatility, like oil.
- *Curb adverse environmental and public health effects:* Energy-related GHG emissions are the dominant cause of climate change. Clean energy technology is the largest—and most essential—

component of mitigation. The shift to clean energy will also reduce the other harmful pollutants associated with energy use, improving health outcomes.

- *Build economic opportunities:* Maintaining our technological edge will enable opportunities to export our clean technologies, products, and services to other countries.[300] Clean energy can be a major opportunity to create new jobs, enable domestic manufacturing, and catalyze industries.[301, 302]
- *Improve energy access and equity:* In many rural and remote places in the United States, communities lack access to reliable and affordable energy services. Advanced energy technologies can support universal energy access, helping boost quality of life and economic development."[303]

Recent analysis suggests programs and investments in technologies supported by initiatives like Mission Innovation could help create significant global opportunities for U.S. businesses and technologies in the following regions of the world:

- *East Asia and the Pacific:* Green buildings—China, Indonesia, the Philippines, and Vietnam show a low-carbon investment potential of $16 trillion.
- *Latin America and the Caribbean:* Offers the next largest opportunity—particularly in sustainable transportation, where the potential for investment in Argentina, Brazil, Colombia, and Mexico is about $2.6 trillion.
- *South Asia:* Opportunities are mostly seen in climate-resilient infrastructure, where $2.5 trillion of opportunities exist in India and Bangladesh.
- *Sub-Saharan Africa:* Represents a $783 billion opportunity—particularly for clean energy in Cote d'Ivoire, Kenya, Nigeria, and South Africa.
- *Eastern Europe:* With its biggest markets—Russia, Serbia, Turkey, and Ukraine—shows a combined investment potential of $665 billion, mostly in energy efficiency and new green buildings.
- *Middle East and North Africa:* The total climate-investment potential for Egypt, Jordan, and Morocco is estimated at $265 billion, "over a third of which is for renewable-energy generation, while 55 percent ($146 billion) is for climate-smart buildings, transportation, and waste solution."[304]

3.4 Environmental Impacts of Electricity on Air, Water, Land Use, and Local Communities

Infrastructure associated with electricity operations has a range of direct impacts to ecosystems and natural resources. The magnitude of impacts depends on how the infrastructure affects endangered species, sensitive ecological areas, or cultural or historic resources; gives rise to visual or aesthetic concerns; or opens new areas to development.[305] Achieving the deep decarbonization of the electricity sector necessary to reach national climate targets will require a significant scaling up of clean energy technology. While Federal, state, and local governments have made strides in assessing the ecological and land-use impacts of current technology—as well as water-use and water-quality impacts—more analysis will be helpful to scale deployment of additional clean energy technologies. Considering the ecological impacts and natural resource implications of new energy technologies in the R&D phase may help avoid the aforementioned impacts and the need to mitigate them. Decreasing land-use and ecological impacts will expand the universe of geographically suited areas for clean energy technology. Further refinement of mitigation policies for those technologies requiring mitigation is also needed.

3.4.1 Air and Water Pollution

The United States has made remarkable progress improving air and water quality under the CAA, the Clean Water Act, and other environmental statutes, but the United States must continue to address emissions, including from the electric sector. For example, the most-polluting power plants still have criteria air pollutant emissions per unit of electricity that are many times larger than the least-polluting power plants.[306]

Direct air pollutants from the electricity system include sulfur dioxide (SO_2), oxides of nitrogen (NO_x), some particulate matter (PM), and mercury and other air toxic pollutants. In addition, these pollutants react in the atmosphere to form secondary pollutants—including acid rain, other PM, and ground-level ozone—that adversely impact air quality. These pollutants increase morbidity and the risk of mortality, reduce agricultural and timber productivity, deteriorate materials, reduce visibility, and harm ecosystems.[307, 308, 309, 310, 311]

In 2009, EPA determined that GHG pollution threatens Americans' health and welfare by leading to long-lasting climate changes that can have a range of negative effects on human health and the environment (Table 0-5).[312] Climate change can "affect human health in two main ways: first, by changing the severity or frequency of health problems that are already affected by climate or weather factors; and second, by creating unprecedented or unanticipated health problems or health threats in places where they have not previously occurred."[313] A U.S. Global Change Research Program report notes: "Given that the impacts of climate change are projected to increase over the next century, certain existing health threats will intensify and new health threats may emerge."[314] In particular, air pollution and airborne allergens will likely increase, worsening allergy and asthma conditions due to climate change. Future ozone-related human health impacts attributable to climate change are projected to lead to hundreds to thousands of premature deaths, hospital admissions, and cases of acute respiratory illnesses each year in the United States by 2030, including increases in asthma episodes and other adverse respiratory effects in children.[315] Ragweed pollen season is longer now in central North America, having increased by as many as 11 to 27 days between 1995 and 2011, which impacts some of the nearly 6.8 million children in the United States affected by asthma and susceptible to allergens due to their immature respiratory and immune systems.[316]

Table 0-5. Summary of Physical Impacts of the Most Common Air Pollutants[317, 318, 319, 320]

	Human Health	Crops and Timber	Materials	Visibility	Recreation
NO_x	Chronic obstructive pulmonary disease		Material deterioration		Eutrophication
	Ischemic heart diseaseIHD				
SO_2	Asthma	Damages to forests	Material depreciation		Damages to forests
	Cardiac				
O_3 (ozone)	Chronic asthma	Crop loss Timber loss	Rubber deterioration		Damages to forests and wilderness areas
	Acute-exposure mortality				
	Respiratory problems				
	Acute asthma attacks				
$PM_{2.5}$	Premature death			Loss of visibility	
	Nonfatal heart attacks				
	Hospital admissions				
	Emergency Room visits for asthma, acute bronchitis, upper and lower respiratory symptoms				
$PM_{10-2.5}$	Chronic bronchitis				

Major impacts of air pollution are delineated by sector and pollutant. $PM_{2.5}$ is particulate matter with a diameter of 2.5 micrometers or less. $PM_{10-2.5}$ is coarse particulate matter with diameter between 10 and 2.5 micrometers.

As of 2014, electricity generation accounted for 64 percent of economy-wide SO_2 emissions and 14 percent of NO_x emissions; power plants were the dominant emitters of mercury (50 percent) and acid gases (75 percent).[321, 322] Within the electricity system, coal combustion accounts for the vast majority of pollutants.[323] While a majority of power plants use scrubbers and other pollution controls to reduce emissions of multiple pollutants, some power plants still do not employ the full suite of available pollution controls or do not control for all pollutants.[324]

Additionally, steam electric power[oo] plants generate wastewater streams from their water treatment, power cycle, ash handling, air pollution control systems, coal piles, and other miscellaneous wastes that can impact ground water and surface water quality.[325] Currently, steam electric power plants account for about 30 percent of all toxic pollutants—including mercury, arsenic, selenium, cadmium, and other toxic metals—discharged into surface waters in the United States.[326] These pollutants can cause severe health and environmental problems in the form of cancer and non-cancer risks in humans, lowered IQ among children, and deformities and reproductive harm in fish and wildlife.[327] In 2015, EPA established new limits on wastewater discharge from power plants that are projected to reduce discharge of the most toxic pollutants by over 90 percent.[328, 329]

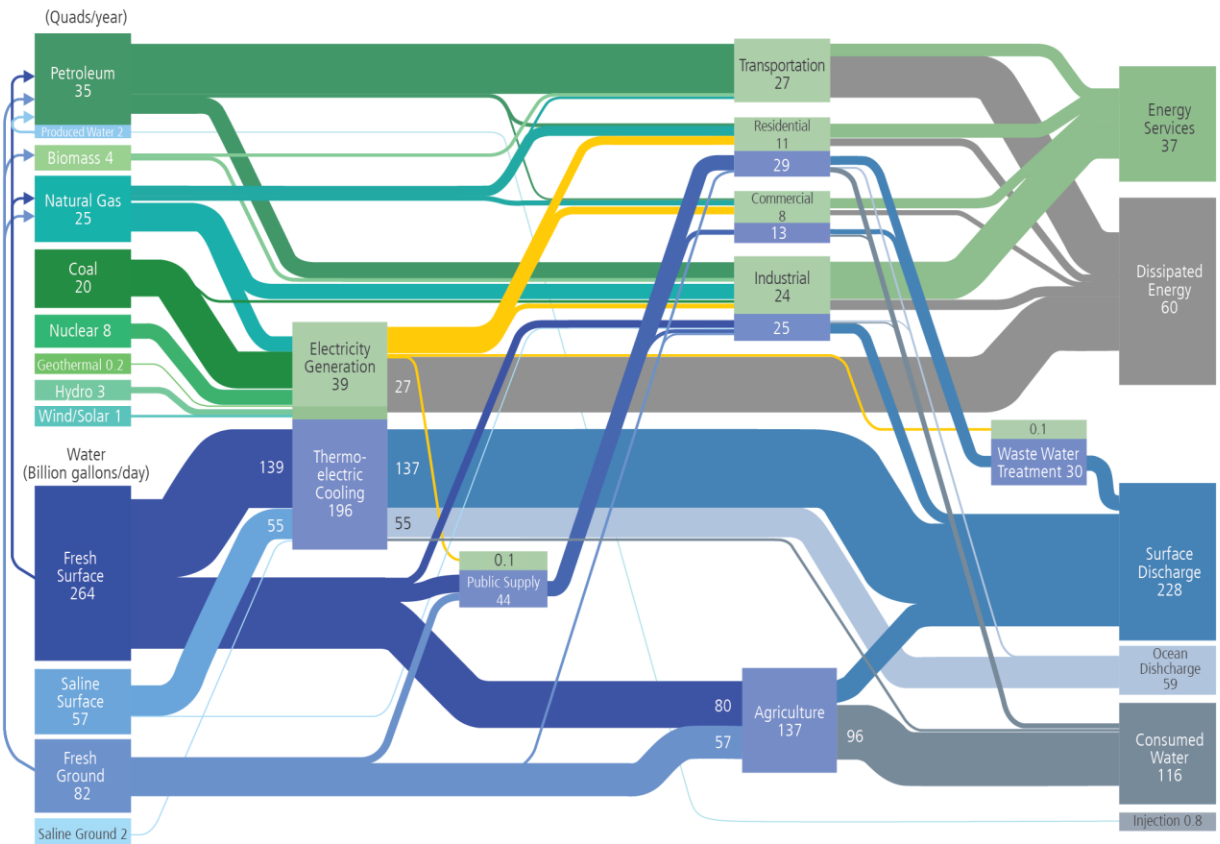
Federal and state governments are continuing their efforts to invest in and incentivize more efficient, less-polluting power plant technologies and to update regulations such as the final Federal Cross-State Air Pollution Update Rule, among other actions. In addition, regulation of CO_2 emissions from power plants is expected to reduce emissions of other air pollutants, creating additional health and environmental benefits in addition to the avoided climate change impacts.[330] The remaining pollution disproportionately affects environmental justice communities (see Section 3.4.7). Environmental justice communities are also disproportionately impacted by climate change because they have less resilience capacity.

3.4.2 Role of Water in Thermoelectric Power Generation

Electricity systems and water systems are strongly interconnected. Water is a critical requirement for many electricity generation technologies. Two-thirds of total U.S. electricity generation—including many coal, natural gas, nuclear, CSP, and geothermal plants—requires water for cooling. In addition, CCUS technologies have significant water demands. From a full-system perspective, the joint reliance of electricity and water systems on each other can create vulnerabilities (e.g., drought impacts thermoelectric generation and hydropower), but this joint reliance can also create opportunities for each system to benefit the other through well-designed integration (see Figure 3-21 for connections between energy and water systems).

[oo] A steam electric power plant is a power plant in which steam is used to generate electricity. In particular, water is boiled to generate steam which, in turn, spins a steam turbine that drives an electrical generator. Most coal, geothermal, solar thermal, nuclear, and waste incineration plants and some natural gas power plants are steam electric power plants.

Figure 3-21. **Hybrid Sankey Diagram of 2011 U.S. Interconnected Water and Energy Flows**[331]



Significant fractions of surface freshwater withdrawals are for thermoelectric cooling and for agriculture, but agriculture consumes more water than thermoelectric cooling consumes. Most electricity is generated for residential, commercial, and industrial use, but significant fractions are used for public water supply and wastewater treatment. The Sankey diagram aids in visualizing these complex data streams and interconnections as a first step toward further analysis.

Several recent trends are particularly important for electricity systems. First, the rising share of wind turbine and solar PV generation requires negligible water for operations. Second, the amount of water *withdrawn* for thermoelectric cooling[pp] has decreased as older plants are decommissioned and more water-efficient or dry-cooled[332] systems are installed. However, water *consumption* in thermoelectric plants is rising as evaporative cooling has become the preferred cooling technology for new plants. In addition, there are water implications of the technology path pursued to address climate change. (See Figure 3-22 for a breakdown of generation, water withdrawal, and water consumption by cooling type.)

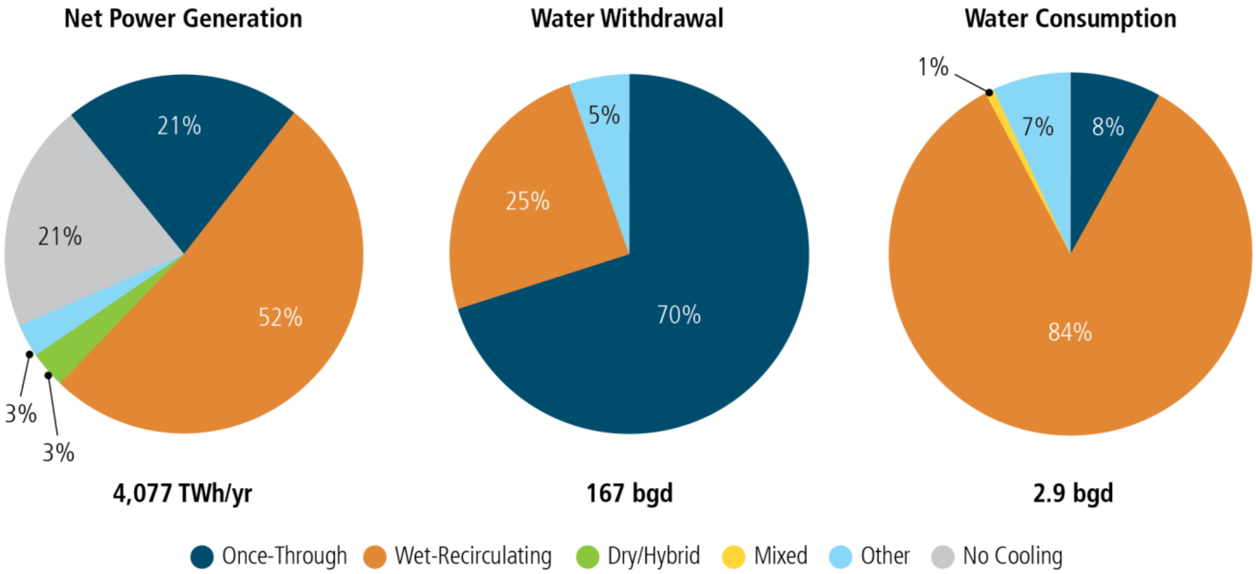
Thermoelectric power generation withdraws large quantities of water for cooling power-producing equipment and condensing steam. It also dissipates large quantities of primary energy due to the process

[pp] "Withdrawal" designates any water diverted from a surface or groundwater source. "Consumed water" designates withdrawn water that is not returned to its source (e.g., because it has evaporated, been transpired by plants, or incorporated into products).

of converting thermal energy to electricity. In 2010,[qq] 45 percent of total U.S. water withdrawals were for thermoelectric cooling alone, making thermoelectric generation the largest withdrawer of combined fresh and saline water nationally.[333] Seventy-two percent of these withdrawals for thermoelectric cooling were fresh surface water, 0.4 percent were fresh groundwater, and the remaining were from saline sources.[334]

The intensity of water use and energy dissipated varies with cooling system technology and generation type, as well as operations. Once-through cooling typically withdraws more water but consumes less than a wet-recirculating system. Dry cooling and wet tower capital and operating costs are significantly higher than for once-through, with dry cooling being the most expensive. Dry cooling units also induce efficiency penalties, raising the possibility of potentially creating tradeoffs between addressing water and climate resilience versus climate mitigation, which could be improved with new technologies.

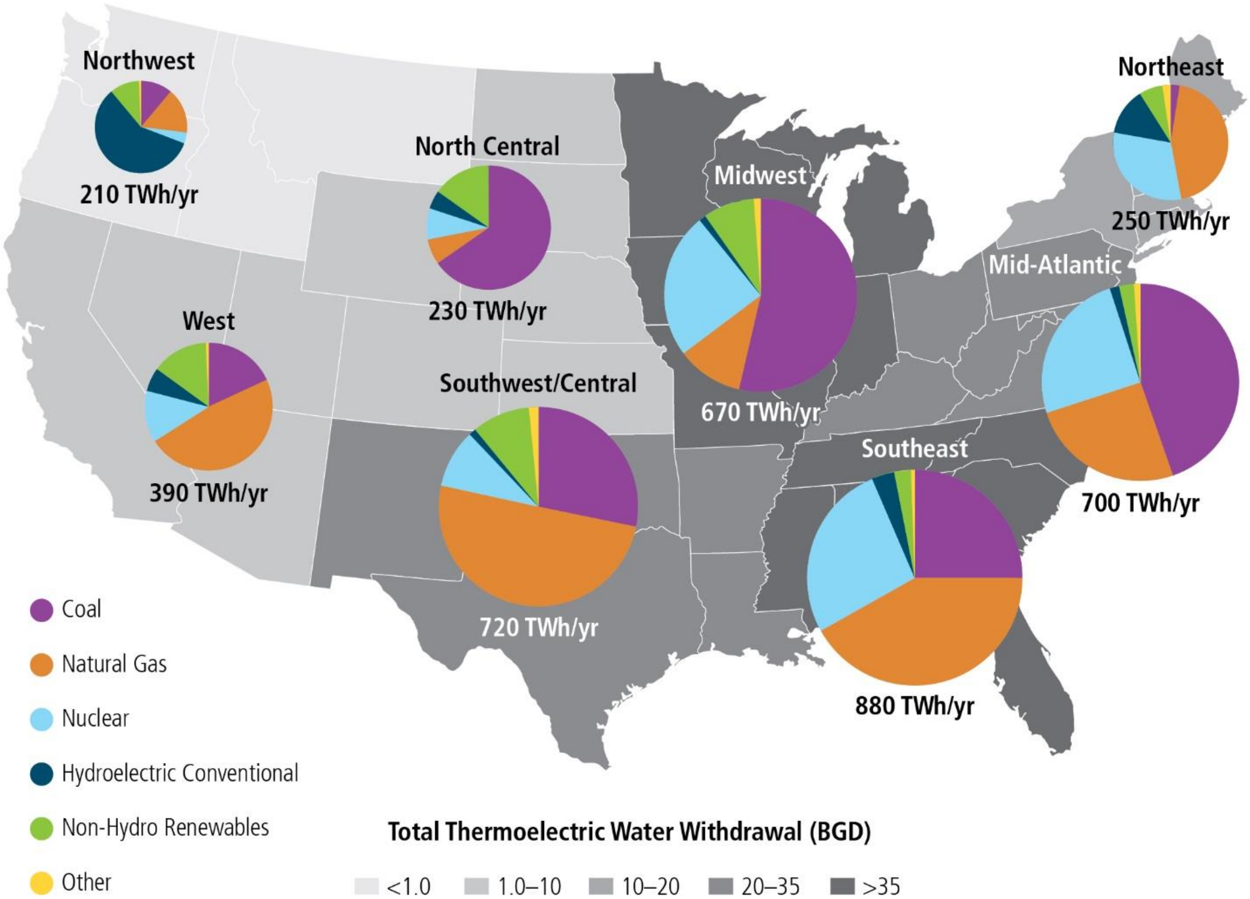
Figure 3-22. U.S. Power Generation, Water Withdrawal, and Water Consumption by Cooling Type, 2015[335, 336, 337, 338]



In 2015, nearly 21 percent of generation used once-through cooling, and 52 percent of generation used wet-recirculating cooling. About 21 percent of the electricity generated—including hydropower, natural gas turbines, and wind turbines—did not require cooling. Water withdrawals for electricity generation totaled 167 billion gallons daily (BGD), the majority of which was withdrawn by once-through cooling. Water consumption totaled 2.9 BGD, with 84 percent of this amount consumed by wet-recirculating cooling.

[qq] The U.S. Geological Survey collects data on water usage by water source every five years and publishes it near the beginning of the next data collection cycle.

Figure 3-23. Water Withdrawal and Generation by Region, 2015[339, 340]

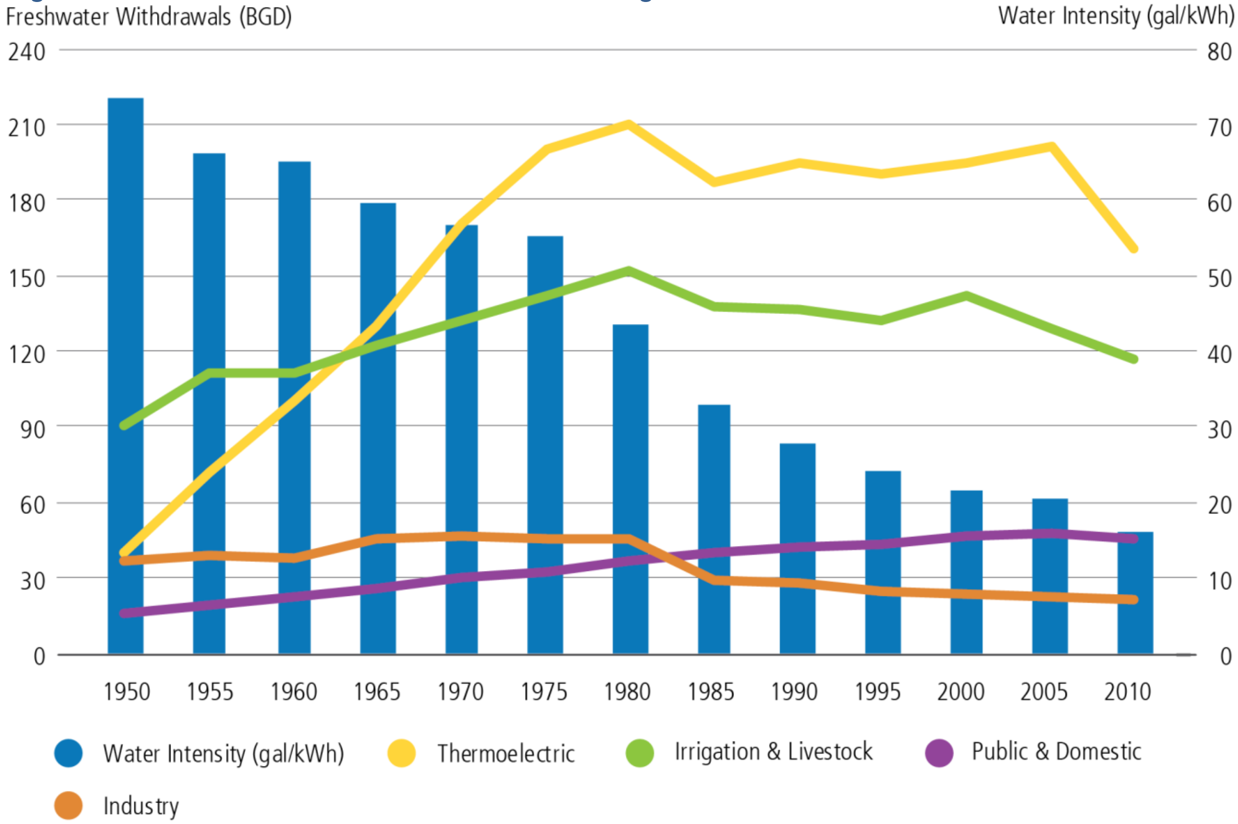


The largest water withdrawal regions are dominated by coal and/or nuclear power generation. The area of each pie chart corresponds to total power generation in that region. "Other" includes petroleum, other fossil fuels, pumped storage, non-biogenic municipal solid waste, batteries, and hydrogen. The eight regions shown in the figure are notional, based upon contiguous groupings of states and their generation mixes, resources, and market structures.

Regionally, water withdrawal and consumption vary significantly across the United States, primarily due to the power generation mix and cooling system type. Figure 3-23 shows the amount of water withdrawal for different types of thermoelectric generation in eight notional regions within the 48 contiguous states. The notional regions are based on contiguous groupings of states and their generation mixes, resources, and market structures. While water withdrawals in all eight regions are dominated by surface water, the Southeast, Southwest/Central, and West regions consume higher levels of groundwater and reclaimed plant discharge water relative to other regions. The regions with the largest water withdrawal are dominated by a combination of coal and nuclear power generation.

Since the 1950s, the amount of water withdrawn per kWh has steadily declined as power generation and cooling technologies have become more efficient over time. The total amount of water withdrawn across all thermoelectric plants, however, has steadily and dramatically increased relative to irrigation, industry, and public use (see Figure 3-24). Much of this increase is due to build-out of once-through cooling systems for the coal and nuclear fleets. By the 1970s, the wet-recirculating system became the dominant cooling system—as these systems withdraw less water, thermoelectric withdrawals leveled off.[341, 342]

Figure 3-24. Water withdrawals for thermoelectric generation and other sectors[343, 344]

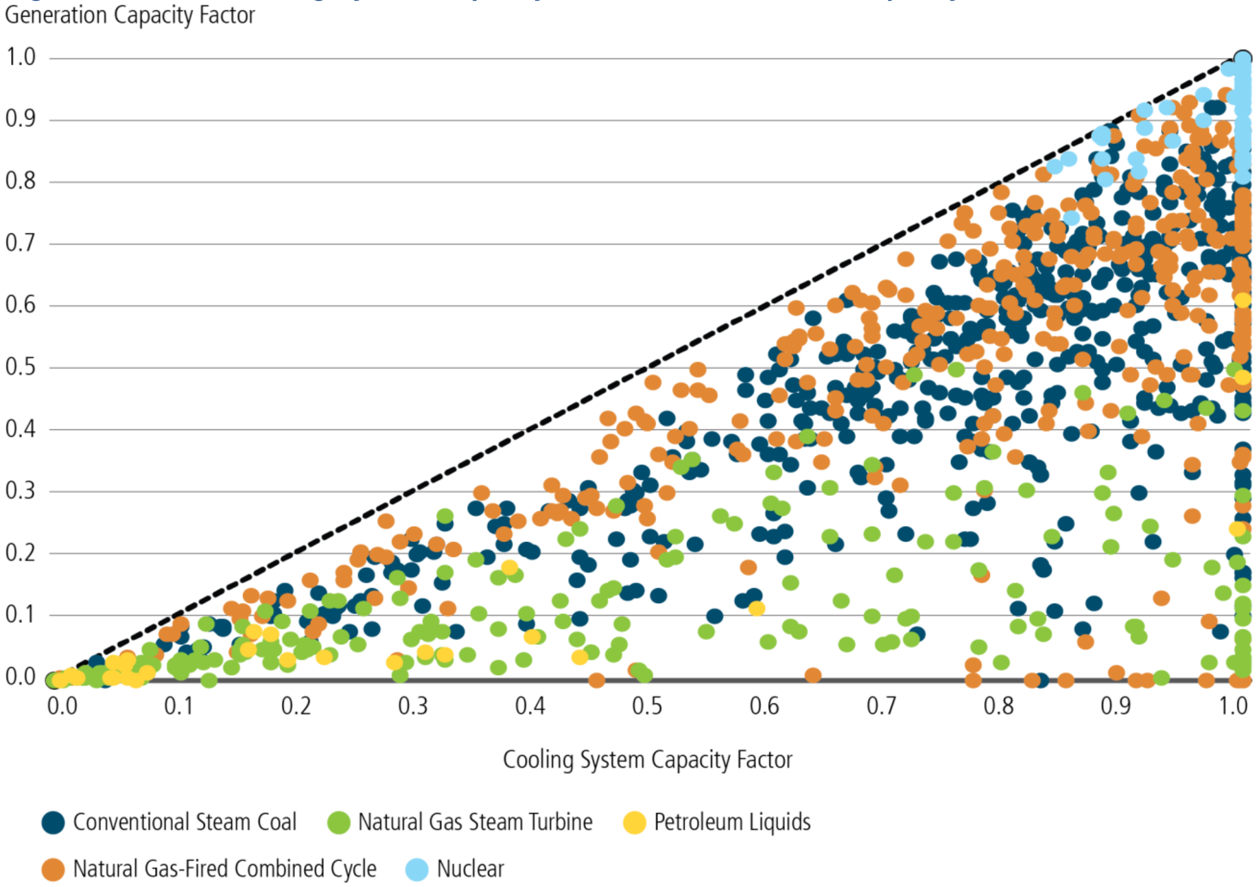


The water intensity of thermoelectric generation (represented by bars) has decreased over time. The total amount of water withdrawn by thermoelectric generation (represented by colored lines) has increased significantly relative to other sectors, but it is now declining.

Some operational practices also affect water use. For example, some peaker power plants, such as natural gas steam turbines with low capacity factors, run their cooling systems for a substantial fraction of the time when they are not generating electricity (as the comparison between capacity factors for generation vs. cooling systems shows in Figure 3-25); they also withdraw a significantly higher amount of water than NGCC plants. There are many potential explanations for this behavior. When plants are not generating electricity, they may decide to keep their cooling systems running in order to minimize biofouling and corrosion, especially in hot and humid climates. They may also opt to keep their cooling system running so they can be responsive to increases in demand from end users or decreases in supply from variable generation. There may be operational best practices that better optimize the trade-offs between load balancing, avoiding biofouling and corrosion, and minimizing water use.

Most types of variable generation do not require water for cooling purposes, but they can put pressure on the system to provide load balancing, usually in the form of dispatchable generation that does require water for cooling. These indirect effects increase the value proposition for other forms of load balancing, such as grid storage or DR.

Figure 3-25. 2015 Cooling System Capacity Factors vs. Generation Capacity Factors[345]



Electricity generators run their cooling systems with varying capacity factors relative to their generating capacity factors. Natural gas steam turbines (Rankine cycle plants)—many likely acting as peakers—run their cooling systems for a substantial amount of time when they are not generating, as do a number of NGCC plants. Plants on the dotted line run their cooling systems with the same capacity factor as their power generation capacity factor (i.e., only when they are generating). Plants that are dispatched primarily during times of peak electricity demand are considered peaking plants and will generally have lower power generation capacity factors. Plants used for baseload electricity will generally have higher power generation capacity factors.

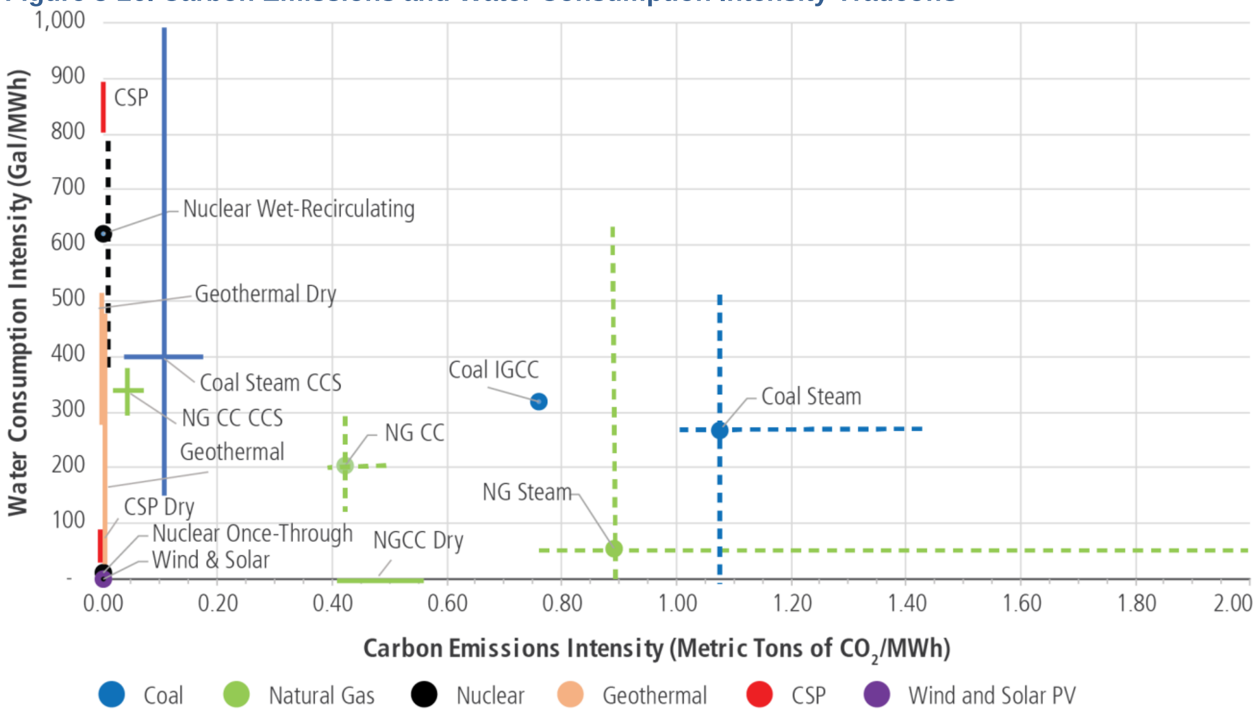
3.4.3 Low-Carbon Generation and Water

The mix of the generation portfolio deployed to reduce GHG emissions will have implications for water withdrawal and consumption. New electricity generation that requires cooling will likely employ recirculating systems, which generally have low water withdrawal but high water consumption. Figure 3-26 shows that some generation technologies can have both low water use and carbon intensities, such as PV and wind, while other generation technologies present tradeoffs between water and carbon emissions.

Some low-carbon technologies, such as nuclear generation, geothermal generation, CSP, and CCUS, require relatively large amounts of water. Incorporating water use and performance metrics into RDD&D funding criteria for these low-carbon technologies could improve the options available for climate mitigation and resilience.

Conversely, dry cooling, which greatly reduces water requirements for thermoelectric cooling, generally induces an energy efficiency penalty, particularly under high-temperature ambient conditions. This increases the carbon intensity of generation, as well as other adoption challenges. However, dry cooling systems offer significant siting flexibility as they do not require access to large volumes of water. At present, there are 74 dry or hybrid cooling systems that provide 53 TWh of net generation in the United States, most of which have been deployed in NGCC plants since 2000. The energy penalty for current dry cooling technologies relative to once-through cooling ranges from 4.2 percent to 16 percent for a representative 400-MW coal-fired plant, depending on plant parameters and ambient conditions.[346] In addition, existing dry (air-cooled) options have higher capital costs and require expanded physical footprints.[347]

Figure 3-26. Carbon Emissions and Water Consumption Intensity Tradeoffs[348, 349, 350, 351, 352, 353]



Some generation technologies (e.g., solar PV and wind) can have both low water and carbon intensities while other generation technologies present tradeoffs between water and carbon emissions. For example, low-carbon technologies, such as nuclear, geothermal, and CSP generation, along with carbon capture and storage (CCS), require large amounts of water. Conversely, dry cooling, which greatly reduces water requirements for thermoelectric cooling, often induces an efficiency penalty, which increases the carbon intensity of generation. Dotted lines represent ranges calculated from data, and solid lines represent ranges from literature values.

Through the Advanced Research in Dry Cooling program, the Advanced Research Projects Agency–Energy (ARPA-E) has invested about $30 million to advance dry-cooling technologies. The program aims to develop dry-cooling technologies that do not consume any water, eliminate efficiency penalties, and do not increase the LCOE by more than 5 percent. Reaching this target would allow for reduced water use for cooling without an additional energy efficiency penalty. In addition, DOE has supported designs for advanced nuclear reactors that use molten salt rather than water as a cooling fluid.

More broadly, there are both opportunities and tradeoffs in energy and water systems integration (e.g., in using treated municipal wastewater for thermoelectric cooling, or in recovering energy from wastewater systems). Making design decisions about how and when to integrate electricity and water systems at multiple spatial and temporal scales is a major challenge that involves a number of actors. Design of more integrated policies and decision making frameworks that take both opportunities and tradeoffs into account could unlock additional value for electricity and water systems.

3.4.4 Land-Use and Ecological Impacts of the Electricity System

The land-use footprint of electricity infrastructures and associated operations has a range of direct impacts to ecosystems and to society more broadly. The magnitude of these impacts depends on how the infrastructure affects endangered species, involves sensitive ecological areas, impacts cultural or historic resources, gives rise to visual or aesthetic concerns, or opens new areas to development.[354] While expanding transmission and distribution (T&D) infrastructure can pose environmental challenges, building new infrastructure can also help to enable significant net environmental benefits. This section discusses considerations that are common to the land-use and ecological impacts of electricity infrastructure, including descriptions of the land-use requirements and ecological impacts of different types of power plants and T&D infrastructure. This section only touches on a few of the most significant ecological impacts that occur upstream of generation, transmission, and distribution. A more detailed examination of these important impacts was beyond the scope of QER 1.2.

3.4.4.1 Land-Use Impacts

For all technology types, the siting of power plants involves the transformation of the existing landscape, the removal of soil and ground vegetation, and the potential for erosion and sedimentation loading to waterways during construction. However, other land-use requirements vary according to the generation infrastructures and their associated operational requirements. Life-cycle land-use impacts of fossil and nuclear plants, when accounting for extraction and waste disposal, are significant; however, the power plants themselves feature relatively small footprints. Conversely, renewable generation life-cycle land-use impacts are minor, with generation facilities having significantly larger footprints.

There is limited literature comparing land-use impacts across generation technologies.[355] One 2009 study, however, sought to normalize life-cycle land requirements for conventional and renewable generation options. This study concluded that among renewable technologies, the PV life cycle required the smallest amount of land, and biomass the largest.[356] Ground-mounted PV systems in areas with high-quality solar resources had no greater requirements than coal-based fuel cycles, which require reclaiming mine lands and securing additional areas for waste disposal. A 2012 NREL report on renewables' land use called for more consistent methodologies to determine the relative impact among generation technologies.[357]

The direct land use for a natural gas power plant is smaller than that required for a coal-fired plant because large structures are not required for fuel storage or emission-control equipment.[358] The land-use footprint of a typical 555-MW NGCC power plant is estimated to use 20 acres, while a typical 360-MW gas turbine simple cycle plant is estimated occupy roughly half as much land area. When the natural gas plants have equipment for carbon capture onsite, then the land-use requirements are estimated to increase by 10 percent.[359] Upstream, the direct land-use requirements—and potential ecological impacts—from natural gas production, transmission, and storage are more than an order of magnitude greater than the footprint of natural gas power plants.[360]

For example, shale gas development involves risks to water quality and quantity, as chemicals necessary for fracking might be leaked or spilled. Should leakage occur, "[t]he risks to local water resources will depend on the proximity to water bodies, the local geology, quantity and toxicity of the chemicals, and how quickly and effectively cleanup operations occur."[361] Induced seismicity by wastewater disposal for natural gas produced through hydraulic fracturing is also a concern.[362]

Upstream, coal mining is conducted both on the surface and underground, and often with significant impacts to the landscape and the ecosystem. Mountaintop mining and valley fills, for instance, can lead to large-scale landscape changes, including the loss of forested areas and displacement and loss of species, as well as significant alterations of stream ecosystems.[363] Similarly, the direct land use for a nuclear power plant is low, but environmental damage resulting from uranium mining—including acid mine drainage and the exposure of surrounding ecosystems to heavy metals[rr]—is possible.[ss]

Although the upstream mining implications of renewable energy sources are less than those associated with many other generation sources, renewable energy systems also require a variety of materials, including commodities like iron/steel, polymer composites, aluminum, and rare earth minerals. Sourcing of these materials require mining of raw materials, with associated risks related to toxicity of associated mine tailings and negative impacts on water used in resource extraction, separation, and processing.

DOE estimates that under a high wind-power deployment scenario by 2050, the total land area affected by wind-power installations would be less than 1.5 percent of the land area of the United States, with the majority (97 percent) of that land area remaining available for multiple purposes.[364] A 2015 Massachusetts Institute of Technology report estimated that all projected U.S. electricity demand in 2050 could be met by PV, assuming storage allowing for all kWh of electricity generated to be used; it would require roughly 33,000 km^2 or 0.4 percent of U.S. land area.[365] This is roughly equal to the area used by surface mining of coal and is less than the land area occupied by major roads. Fitting current existing U.S. rooftop area with PV could meet approximately 60 percent of the Nation's projected 2050 electricity needs.[366] Similarly, NREL estimated that the technical potential exists for rooftop PV to generate 1,432 TWh of electricity, or 39 percent of total annual electricity sales.[367]

3.4.4.2 Wildlife Impacts

Power generation can have adverse impacts on wildlife. There are a variety of mitigation strategies available to alleviate such impacts and, as discussed below, mortalities attributed to power generation are significantly fewer than those than can be attributed to natural predators and collisions with buildings.

Available data on wildlife impacts associated with coal-fired power plant operations is limited, although one study[368] estimates that coal-fired power plants cause roughly the same or more avian mortalities per GWh generated than wind turbines. Factoring in projected climate change impacts, avian mortalities attributed to coal-fired electricity were estimated to be far greater than those attributed to other electric generation technologies.[369]

Nuclear power generation poses a risk to avian populations, which can be exposed to toxic waste ponds at uranium mining and milling facilities and collide with nuclear cooling towers.[370] Utility-scale solar energy development can affect birds and avian communities directly through fatality or indirectly through degradation, loss, or fragmentation of habitat. In general, direct fatalities are related to collisions or solar flux.[tt, 371] Collisions may occur with all types of solar energy technologies, but solar flux effects on birds

[rr] Uranium mining in the United States is regulated by the Atomic Energy Act of 1954, as amended (42 U.S.C. §§ 2011-2021, 2022-2286i, 2296a-2297h-13). These regulatory actions protect the health and safety of the public and the environment during the active life of a uranium recovery operation and after the facility has been decommissioned. Licensing may require licensees to take preventative measures prior to starting operations, including well tests, monitoring, and development of procedures that include excursion response measures and reporting requirements. NRC issued a "Generic Environmental Impact Statement for In-Situ Leach Uranium Mining Facilities" (NUREG 1910) in May 2009: http://www.nrc.gov/materials/uranium-recovery/geis.html.

[ss] The amount of uranium mining in the United States is currently very low.

[tt] There is not a thorough understanding of potential impacts of solar facilities on avian species or the effectiveness of mitigation measures at this time. Consistency and standardization in avian monitoring and reporting protocols could be improved, and additional systematic data on avian fatalities are needed to decrease uncertainty about potential impacts. The preeminent report on this topic, published in 2015, calls for creating a solar-avian science plan to improve the scientific value of avian mortality data, inform decisions about project siting and design, and develop an avian risk assessment tool to improve understanding of impacts and inform project-specific mitigation decisions. Leroy J. Walston, Jr., et al., *A Review of Avian Monitoring and Mitigation Information at Existing Utility-Scale Solar Facilities* (Argonne, IL: Argonne National Laboratory, April 2015), ANL/EVS-15/2, http://www.evs.anl.gov/downloads/ANL-EVS_15-2.pdf.

have been observed only at facilities with towers equipped to concentrate solar power. A recent study estimated that approximately 6,000 birds died across the five square miles of California's Ivanpah solar thermal facility last year;[372] none were endangered. For comparison, domestic cats kill 1.4 to 3.7 billion birds per year, and between 365 million to 988 million birds are estimated to die annually in the United States from building collisions.[373] The impacts on avian and bat populations are the principal ecological concerns associated with wind development for land-based wind projects. Effects on marine life are the principal concern for offshore wind.

DOE and the Bureau of Land Management (BLM) have jointly developed guidance to minimize environmental impacts—including impacts to wildlife—during the siting, construction, and operation of utility-scale solar facilities on public lands. BLM identified specific locations well suited for utility-scale production of solar energy that minimize wildlife impacts. Similarly, the DOE guidance integrates wildlife and environmental considerations into its analysis and selection of projects that it will financially support.[374]

Investments to develop cost-effective technologies that can reduce wildlife impacts are offering new avian deterrence technologies (e.g., tower coatings and ultrasonic transmitters) and mitigation techniques that will help minimize environmental impacts to sensitive wildlife in the future.[375]

The DOE Wind Vision report[376] finds that annual bird mortalities due to wind turbines (0.2 million birds/year) are much lower than those associated with other engineered structures and far lower than those killed by domestic cats. Most studies estimate the bat fatality rates due to wind turbines to be less than 10 bats/MW/study period.[377] With the increase in wind-power generation, the wind industry and regulatory agencies have worked to minimize the impacts of wind projects on migratory birds and other species of concern and their habitats.[uu]

Hydroelectric power can also significantly impact aquatic ecosystems, with fish and other organisms injured and killed by turbine passage. Mechanisms of mortality and injury are varied (e.g., strike, barotrauma,[vv] shear, turbulence). Reservoir water is usually more stagnant than normal river water, which can lead to algae blooms and other aquatic weeds crowding out native aquatic life. DOE has sponsored research to mitigate wildlife impacts of conventional hydropower (e.g., R&D of turbine designs that minimize fish deaths for fish that pass through the turbine).[378] Many species of fish, such as salmon, swim from the sea upstream to spawn, and dams can block their way. Approaches like the construction of fish ladders and elevators help fish to move around dams to upstream spawning grounds. To address these challenges, the Federal Government is investing in tools and methods to develop, demonstrate, and

[uu] The Fish and Wildlife Service is one of the agencies responsible for this activity, and, in consultation with industry, it has acted to suggest design modifications for towers and to establish voluntary guidelines and guidance to protect bald and golden eagles, as well as the Indiana bat. See Fish and Wildlife Service, *Indiana Bat: Section 7 and Section 10 Guidance for Wind Energy Projects* (Fish and Wildlife Service, 2011), http://www.fws.gov/midwest/endangered/mammals/inba/WindEnergyGuidance.html. DOE recently issued two funding opportunity announcements to develop mitigation technologies for eagles and bats. In December 2016, the Fish and Wildlife Service finalized a rule that revised its permitting processes and monitoring requirements to improve the protection of eagle populations. Changes to the rule "include revisions to permit issuance criteria, compensatory mitigation standards, criteria for eagle nest removal permits, permit application requirements, and fees." Laury Parramore, "Service Announces Final Rule to Further Conserve, Protect Eagles through Revised Permitting, Monitoring Requirements," Fish and Wildife Service, December 14, 2016, https://www.fws.gov/news/ShowNews.cfm?ref=service-announces-final-rule-to-further-conserve-protect-eagles-through-&_ID=35912.

[vv] As a fish passes through a dam, it can experience barotrauma—significant changes in pressure that can result in internal injuries or death. Richard S. Brown, Alison H. Colotelo, Brett D. Pflugrath, Craig A. Boys, Lee J. Baumgartner, Z. Daniel Deng, Luiz G. M. Silva, et al., "Understanding, Barotrauma in Fish Passing Hydro Structures: A Global Strategy for Sustainable Development of Water Resources," *Fisheries* 39, no. 3 (2014): 108–122, http://dx.doi.org/10.1080/03632415.2014.883570.

validate environmentally and fish-friendly technologies, such as turbines that better allow for the downstream passage of fish and aerating turbines that will enable operators to better meet environmental standards while increasing electricity generation. Computational tools that estimate fish passage risk are also helping ensure that biological impact is considered during turbine design.[379]

3.4.4.3 Waste Impacts

Coal and nuclear power plants produce the largest amount of solid waste during generation. CCRs are the second most abundant waste material in the United States after household waste.[380] CCRs are generally disposed onsite at the power plant, while some are used for beneficial purposes.[381] In 2014, U.S. plants produced 130 million tons of coal ash,[382] which is a byproduct of conventional coal-fired generation. Naturally occurring radioactive constituents, such as uranium, are also found in coal ash.[383, 384] Onsite coal ash impoundment ponds can breach, impacting surrounding ecosystems and watersheds, an issue that EPA continues to address through its rulemaking process.

Nuclear waste is stored at the reactor site where it is generated. In contrast, natural gas and oil generation produce limited amounts of chemical and air pollution control waste, and renewable technologies produce almost no waste during generation. Additional information on waste as it relates to decommissioning can be found later in this chapter in Section 3.4.8.

3.4.4.4 Other Ecological Impacts

Additional ecological considerations for wind include impacts from associated infrastructure (e.g., roads, transmission lines, substations). Noise, visual impacts (from blinking lights and from wind turbines themselves), and property values are all concerns raised by communities with wind development. For onshore wind, a Lawrence Berkeley National Laboratory study found that there was no impact by wind turbines on residential property value.[385]

Ecosystem impacts from hydroelectric power plants depend on a river's size and flow rate; climate and habitat conditions; the type, size, design, and operation of the plant; and whether the plant is located upstream or downstream of other projects on the same river.[386] Most water quality concerns have to do with how reservoirs affect oxygen levels downstream (since significant aeration occurs in process).

There are also ecological impacts associated with geothermal generation. When large amounts of geothermal fluids are withdrawn and injected below the earth's surface, induced seismicity becomes a concern. If induced seismicity occurs, it is typically less than magnitude 2.5 on the Richter scale (earthquakes usually are not felt below 3.5).[387]

To address concerns about induced seismicity related to enhanced geothermal systems, DOE commissioned experts to author the Induced Seismicity Protocol, a living guidance document for geothermal developers, public officials, regulators, and the general public that details useful steps to evaluate and manage the effects of induced seismicity related to geothermal projects.[388]

3.4.4.5 Land-Use and Ecological Impacts of Electricity T&D

While the environmental impacts of T&D tend to be smaller than generation impacts, they are not negligible.[389] As T&D assets are not large point sources of pollution and are geographically expansive, their impacts also may not be well characterized.[390] T&D systems have an array of direct and indirect environmental impacts, which can be divided between the impacts associated with construction and those related to operation of the electric grid. The ecological impacts of transmission lines can be weighed against transmission lines' benefits. For example, transmission lines connect remotely located, lower-emitting generation sources to load centers, and clearings for transmission lines create firebreaks, reducing the impacts of wild fires and improving emergency access.

New power lines, access roads, and associated equipment placed in undeveloped areas can create substantial environmental impacts, including the disturbance of forests, wetlands, and other natural areas. Adjusting proposed routes of overhead power lines can reduce environmental impacts.[391] Choosing a different type of pole structure or modifying construction methods can reduce environmental impacts. Right-of-way issues can be minimized by using corridor-sharing routes during the design phase.

Putting power lines underground can limit the visual impact of overhead lines. Burying low-voltage distribution lines is common in residential areas. Burying transmission lines, however, is uncommon because it is 2–10 times more expensive than building an overhead line.[392] T&D infrastructure requirements for DG systems have smaller footprints. DG units are closer to end users, reducing the need for new or expanded transmission. DG systems can require expanded transformer and substation capacities (the average cost of updating a substation is $40/kilovolt-ampere).

Avian mortalities from collisions with transmission lines and related infrastructures are an environmental cost of the T&D system. In addition to reducing bird populations, collisions and electrocutions can produce outages. Bird collisions vary by habitat type, species size, and scavenging rates, and they appear to be higher during migration. Adverse effects on certain birds (e.g., electrocution of eagles) may result in penalties.[393] One inventory of bird mortality from transmission lines across Canada, about half the size of the U.S. system, reported 2.5 to 25.6 million bird deaths annually.[394] In the United States, research conducted by the Fish and Wildlife Service found that power lines alone might kill up to 175 million birds annually.[395] Proactive planning can help reduce these impacts on avian and other wildlife populations.

3.4.4.6 Mitigation of Environmental Impacts

There are several existing environmental laws designed to help mitigate the environmental impacts and concerns outlined above. Applicable Federal laws include the CAA,[396] the Clean Water Act[397] and the Endangered Species Act.[398] Any Federal action involving new infrastructure requires the responsible Federal official to consider the potential environmental impacts of the proposed action and any reasonable alternatives.[399] This requirement is specified in the National Environmental Policy Act (NEPA) of 1969 and the Council on Environmental Quality Regulations for Implementing the Procedural Provisions of NEPA.[400] The complexity associated with obtaining the environmental permits necessary to build new infrastructure will differ depending on the implications of the proposed facility's proximity to sensitive air, water, wildlife, and cultural resources.

The first installment of the QER (QER 1.1) found that while expanding T&D infrastructure can pose environmental challenges, building new infrastructure can also lead to significant net environmental benefits. For this reason, agencies across the Federal Government are engaged in several initiatives to modernize the Federal role in electric transmission permitting and project review.[401] In their analyses, permitting agencies typically[ww] consider mitigation requirements that may be imposed as conditions to address unavoidable environmental harms. Decades of experience with siting energy T&D infrastructure have produced various methods for offsetting impacts to affected communities and ecosystems, including avoidance, minimization, and compensation. These methods are summarized QER 1.1 and are reproduced in the box below.

[ww] Agencies must consider mitigation when completing an environmental impact statement, and mitigation is often considered when completing an environmental assessment.

Mitigating Environmental Impacts[402]

- Mitigation is an important mechanism for agencies to use to avoid, minimize, rectify, reduce, or compensate the adverse environmental impacts associated with their activities.[403, 404] Federal agencies typically rely upon mitigation to reduce environmental impacts through modification of proposed actions and consideration and development of mitigation alternatives during the National Environmental Policy Act process.[xx]
- Mitigation is important to Federal agencies managing public lands, which impose a responsibility to sustain an array of resources, values, and functions. For example, public lands contain important wildlife habitat and vegetative communities—in addition to recreational opportunities and ecosystem services, cultural resources, and special status species. These lands are managed for the use and enjoyment of present and future generations. The location, construction, and maintenance of energy infrastructure should avoid, minimize, and, in some cases, compensate for impacts to these public resources, values, and functions. Mitigation is of critical importance to agencies responsible for protecting the Nation's waters.[405] Applying this mitigation hierarchy early in transmission and distribution infrastructure planning provides better outcomes for the impacted resources, values, and functions.[406]
- Resource-specific mitigation measures can be applied to avoid or minimize impacts from a pipeline or an electric transmission project. In order to identify and implement appropriate mitigation measures, first the potential impacts of a project on a specific resource must be assessed. Then, project-specific and site-specific factors must be evaluated to determine whether the impact can be avoided or mitigated, what action can be taken, how effective the mitigation measure will be, and the cost effectiveness of the measure.

3.4.4.7 Mitigating Impacts through Siting and Permitting of Electricity Infrastructure

Most siting and permitting decisions are made at the state and local levels, but the transformation of the U.S. electricity system requires effective siting and permitting capabilities at all levels of government. Planning and permitting new transmission infrastructure, including managing ecological impacts across jurisdictions and with a wide range of stakeholders, is uniquely challenging. Federalism and the interplay of state and Federal law create overlapping jurisdictional lines. State, local, and tribal governments, assisted by Federal agencies, need to build capacity to minimize safety and security consequences, as well as protect the environment, while limiting permitting-related delays.[407, 408] Local governments may adopt zoning requirements that differ from state regulations or even the regulations of neighboring communities.[409] Tribal governments become participants in permitting decisions if a project may disrupt cultural or historic properties or resources.[410]

For any project that involves a Federal action (e.g., if a proposed project would be sited on Federal land or partially financed with Federal funds), the responsible Federal agency is required by NEPA to evaluate potential social and environmental impacts of the proposed action and consider reasonable alternatives.[411] Since multiple Federal agencies can be involved with permitting T&D infrastructure, the Obama Administration has taken steps to modernize Federal permitting and review processes.[412] Active coordination between Federal, state, and local governments enables well-informed decision making, striking a fair balance between a broad range of public and private interests.

[xx] The Council on Environmental Quality's NEPA regulations require agencies to identify in their Record of Decision any mitigation measures that are necessary to minimize environmental harm from the alternative selected (40 C.F.R. § 1505.2(c)). The NEPA analysis can also consider mitigation as an integral element in the design of the proposed action. The regulations further state that a monitoring and enforcement program shall be adopted where applicable for any mitigation (40 C.F.R. § 1505.2(c)).

3.4.5 Federal and State Initiatives to Modernize Permitting and Review Processes

The Federal Government is undertaking several actions to reduce the aggregate permitting and review time for infrastructure projects, while improving environmental and community outcomes. This includes a number of Federal and regional initiatives (outlined in Table 3.6) that are designed to support better decision making in the following ways:

- Facilitate better coordination between permitting authorities at all levels of government
- Develop and publish relevant information, data, and tools
- Support infrastructure planning and establish rights of way for energy projects
- Conduct technology R&D.

Table 0-6. Federal and Sub-National Initiatives to Modernize Electric Infrastructure Permitting and Review Processes[413]

Initiative Title	Description (Scope and Specific Focus Areas)
Facilitate Better Coordination between Permitting Authorities, Increase Transparency	
Establishing an Implementation Plan to Modernize Permitting	National; Federal plan includes four strategies, 15 reforms, and nearly 100 near-term and long-term milestones, established by Presidential Memorandum
Improving Performance of Federal Permitting and Review of Infrastructure Projects	National; Executive Order 13604 to improve the efficiency and transparency of permitting and review processes for infrastructure projects while producing measurably better outcomes for communities and the environment
Transforming the Nation's Electric Grid through Improved Siting, Permitting, and Review	National; developing an integrated interagency pre-application process for significant onshore electric transmission projects requiring Federal approval, identifying and designating energy corridor
Creating a Permitting Dashboard	National; online database to track the status of Federal environmental reviews and authorizations for projects covered under Title 41 of the Fixing America's Surface Transportation Act
Establishing an Interagency Rapid Response Team for Transmission	National; improve Federal interagency coordination, tribal consultation, and conflict resolution for challenging transmission projects
The Western Governors Association Regulatory and Permitting Information Desktop Toolkit	Western United States; includes wiki platform for stakeholder and agency collaboration
Integrated Interagency Pre-application Process	National; DOE final rulemaking to improve project planning process
Fixing America's Surface Transportation Act	National; Title 41 establishes the Federal Infrastructure Permitting Improvement Steering Council to inventory major infrastructure projects that are subject to NEPA and improve the review process
Publish Information, Data, and Tools	
EPA's NEPAssist	National; web-based mapping tool
Fish and Wildlife Service's Information, Planning, and Conservation Tool	National; help identify endangered and threatened species before beginning project design
Army Corps' Federal Support Toolbox	National; "one-stop shop" online water resources data portal

Initiative Title	Description (Scope and Specific Focus Areas)
Eastern Interconnection States Planning Council's Energy Zones Mapping Tool	Eastern United States; includes 273 geographic information system data layers and links to key resources
Energy Zones Mapping Tool for the Eastern Interconnection Planning Collaborative	Eastern United States; mapping clean energy resources and transmission
Western Electricity Coordinating Council Environmental Data Viewer	Western United States; interactive transmission planning tool
Support Infrastructure Planning	
Undertaking landscape- and watershed-level mitigation and conservation planning	National; environmental mitigation and resource protection at the landscape and watershed levels
Speeding infrastructure development through more efficient and effective permitting and environmental review	National; Presidential Memorandum calling for expedited review of priority projects and improved accountability, transparency, and efficiency
Memorandum of Understanding regarding transmission siting on Federal lands	National; aims at reducing approval time and reducing barriers to siting new transmission lines
Designating corridors for pipelines, electric transmission lines, and related infrastructure	Western United States; Energy Policy Act of 2005 Section 386 establishes rights-of-way on Federal land to promote energy development, resolve resource disputes, and reduce congestion
Desert Renewable Energy Conservation Plan	California; Federal and state collaboration on landscape-level plan streamlining renewable development while conserving unique and valuable desert ecosystems
Technology R&D	
Promoting grid modernization, DOE	National; Enhance security capabilities and stakeholder support

A number of federal and regional initiatives are designed to improve the electric infrastructure permitting and review process. Improved coordination not only reduces permitting and review time, but also improves environmental and community outcomes. These initiatives include the facilitation of coordination between authorities and increased transparency, new tools to disseminate information effectively, the support of infrastructure planning, and technology R&D.

3.4.6 Addressing Impacts of Increased Deployment and New Clean Energy Technologies

Increased deployment of existing clean energy technologies and the development of new clean energy technologies will require refinement of existing mitigation policies, which were developed before these technologies became available, as well as new approaches to mitigation. Including analyses of land-use and ecological impacts in the R&D process for new technologies could avoid most impacts and decrease the need for mitigation.

Improving environmental outcomes from infrastructure siting requires the joint efforts of agencies at all levels of government and the private sector.

Recent Transmission Line Approvals

- **Clean Line Plains & Eastern Project**:[414] In March 2016, Secretary Moniz announced that the Department of Energy (DOE) would participate in the development of the Plains & Eastern Clean Line Project (Clean Line), a major clean energy infrastructure project. The Clean Line project taps abundant, low-cost wind generation resources in the Oklahoma and Texas panhandle regions to deliver up to 4,000 megawatts (MW) of wind power via a 705-mile direct current transmission line—

enough energy to power more than 1.5 million homes in the mid-South and Southeast United States.

The Clean Line project will include a 500-MW converter station in Arkansas that will allow the state to access the low-cost renewable energy supplied from the project. Currently, Arkansas has no utility-scale wind generation facilities and none under construction. Furthermore, as a condition of its participation, DOE required that Clean Line make payments to localities for any otherwise-taxable land and assets that are owned by the Federal Government.

- **Great Northern Transmission Line**:[415] In November 2016, DOE announced the issuance of a Record of Decision and Presidential Permit for the Great Northern Transmission Line. The 224-mile, overhead alternating current transmission line will bring up to 883 MW of hydropower from Manitoba Power in Canada to Grand Rapids, Minnesota, and will deliver wind power generated in North Dakota to Manitoba Power in Canada. The project has the potential to provide enough reliable, affordable, and carbon-free electricity to serve approximately 600,000 residential customers in the Upper Midwest.
- **New England Clean Power Link**:[416] In December 2016, DOE announced the issuance of a Record of Decision and Presidential Permit for the New England Clean Power Link Transmission Line. The 154-mile underground and underwater direct current transmission line will bring up to 1,000 MW of hydropower from Quebec, Canada, to southern Vermont. The project has the potential to provide enough reliable, affordable, and carbon-free electricity to serve approximately 1 million residential customers in New England.

3.4.6.1 Data and Analytical Needs for a Clean Electricity System

In general, it is important to have authoritative, unbiased data in order to make informed Federal policy decisions, but this is also important to empower other public- and private-sector entities at all levels to identify cost savings, provide better services, effectively plan for the future, make research and scientific discoveries, etc. DOE has done well to provide relevant electricity data for many years, most notably via the Energy Information Administration. However, attempts to address a host of emerging issues and pursue key policy objectives in the electricity sector have uncovered data issues that are inhibiting such efforts by actors at all levels of government.

Ecological and other environmental impacts, specifically, can be reduced by improving availability, quality, harmonization, standardization, and accessibility of relevant data to inform decision making. Some data sets exist already, including Tethys,[417] a growing compendium of information and data exchanges on the environmental effects of wind and marine renewable energy technologies,[418] and the Wind-Wildlife Impacts Literature Database, a searchable document collection focusing on the impacts to wildlife from a variety of technologies.[419] However, relevant data, if available, can be plagued with quality issues, and there are often spatial and temporal disparities between related data sets that make analysis difficult.

There is a need for additional data and analytical tools on updated life-cycle analysis using consistent methodologies, as well as studies that attempt to monetize external costs[420] associated with land-use requirements and ecological impacts. More research and increased availability of data would improve the transparency of environmental impacts to developers, regulators, and the public, and help inform more effective strategies for mitigating ecological impacts of electricity infrastructure and operations.

Including analysis of land and ecosystems in the R&D process could decrease the need for mitigation. New technologies with no adverse effects on ecosystems would unlock further areas where that technology could be deployed. As the United States and other countries accelerate clean energy innovation through Mission Innovation, including land-use and ecosystem impacts in Mission Innovation could provide a more holistic assessment of the environmental and ecological effects of new clean energy technologies.

3.4.6.2 Multiple Uses for Rights of Way: Repowering and Repurposing Degraded Lands or Brownfields

Electricity infrastructure can be sited at less environmentally sensitive locations, such as Superfund sites, brownfields, landfills, abandoned mining land, or existing transportation and transmission corridors. Through its cataloging of Federal and state tracked contaminated lands, landfills, and mine sites, EPA has identified thousands of potential sites that could potentially ameliorate incremental environmental impacts.[421] Comprehensive land-use planning exercises have also identified areas appropriate for development, such as the California Desert Renewable Energy Conservation Plan and the DOE-BLM Solar Programmatic Environmental Impact Statement. States and Federal agencies could assess the amount of land suitable for multiple simultaneous uses, including the installment of clean energy technologies. Zoning laws could allow multiple land uses as a factor in permitting decisions for clean energy technologies.

3.4.6.3 Programmatic Environmental Planning and Land-Scale Impact Assessments

The trend has been to consider mitigation through programmatic environmental impact statements (PEIS) and landscape scale impact assessment, replacing a more project-orientated focus. A November 2013 Presidential Memorandum outlined further mitigation principles for Federal agencies, including requiring agencies to set a "no net loss" or "net benefit" goal. Subsequent Department of the Interior guidance on landscape-scale mitigation supported examining project impacts by considering the range of the resource in the context of the larger landscape where the project would be built. Landscape-scale strategies consider impacts across ecosystems and administrative boundaries, and give a more comprehensive picture than studies focused narrowly on impacts on a project-by-project basis. This approach is being applied to a variety of major infrastructure development projects, including transmission and other electricity projects. The Fish and Wildlife Service uses landscape-scale analysis to protect the golden eagle, among other species, defining its "no net loss" policy to require every golden eagle killed at a wind plant to be offset by reducing eagle mortality from another source or by increasing eagle productivity.[422]

BLM also conducts PEIS for geothermal explorations or solar energy development in six southwestern states. PEIS evaluate environmental impacts of a variety of individual projects over a long time frame and a large geographic area.[423] Land-use and ecological impacts of energy technologies should be assessed on a larger scale, and the necessary cooperation across jurisdictions should be expanded, especially as impacts on wildlife could be felt far away from the original site of the deployed technology.

3.4.7 Electricity and Environmental Justice

Populations of concern—including low-income communities and some minority and tribal communities—are more vulnerable to the air- and water-quality impacts of the electricity system. These communities are also disproportionately vulnerable and less resilient to the impacts of climate change. These communities may have greater exposures due to their proximity to sources of pollution; may be inherently more sensitive to environmental impacts of pollution due to higher baseline risks, such as poor overall health; and typically have lower capacity to adapt to the impacts of pollution and extreme weather.[424] For example, a greater percentage of minorities and people living below the poverty level live within a 3-mile radius of coal- and oil-fired power plants, compared to the U.S. population overall.[425] Additionally, existing health disparities and other inequities in these communities increase their vulnerability to the health effects of degraded air quality and climate change.[426]

Populations with the greatest sensitivity to the impacts of air pollution from power generation include children, the elderly, African Americans, and women.[427] Several factors make children more sensitive to air quality impacts, including lung development that continues through adolescence, the size of children's airways, their level of physical activity, and body weight. Ground-level ozone and PM are associated with increased asthma episodes and other adverse respiratory effects in children.[428] Minority adults and children bear a disproportionate burden associated with asthma, as measured by emergency hospital visits, lost work and school days, and overall poorer health status.[429]

Environmental justice concerns have been addressed in recent regulatory actions affecting power plant emissions, wastewater discharges, and onsite solid waste impoundment.[430, 431, 432] In many cases, these rulemakings have provided the opportunity to reduce existing disparities in health impacts. For example, the Mercury and Air Toxics Standard requires power plants to limit their emissions of toxic air pollutants like mercury, arsenic, and metals, which disproportionately impact certain communities. In addition, Executive Order 12898 requires Federal agencies to consider environmental justice in regulatory, permitting, and enforcement activities. Also, in developing the CPP, EPA took steps to ensure that vulnerable communities were not disproportionately impacted by the rule and that the rule's benefits, including climate benefits and air quality improvements, were distributed fairly.

The Federal Interagency Working Group on Environmental Justice's "Promising Practices for EJ Methodologies in NEPA Reviews"[433] contains successful ideas across nine areas, from which all Federal agencies can draw to develop their approaches to address environmental justice in the NEPA process:

- Meaningful engagement
- Scoping process
- Defining the affected environment
- Developing and selecting alternatives
- Identifying minority populations
- Identifying low-income populations
- Impacts
- Disproportionately high and adverse impacts
- Mitigation and monitoring.

3.4.8 Decommissioning of Generation Assets

Infrastructure expansion can improve environmental performance by replacing higher-polluting with lower-polluting technologies.[434] Because of their unique environmental concerns, nuclear power plants have strict, mandatory guidelines, payment processes, and monitoring for decommissioning activities, while in general, other generation assets do not. There are multiple ways to improve and expedite end-of-life-cycle processes while also improving environmental and societal outcomes.

Currently, the changing electricity sector is causing the closure of many coal and nuclear plants in a shift from recent trends. From 2000 through 2009, power plant retirements were dominated by natural gas steam turbines. Over the past 6 years (2010–2015), power plant retirements were dominated by coal plants (37 GW), which accounted for over 52 percent of recently retired power plant capacity.[435] Over the next 5 years (between 2016 and 2020), 34.4 GW of summer capacity is planned to be retired, and 79 percent of this planned retirement capacity are coal and natural gas plants (49 percent and 30 percent, respectively). The next largest set of planned retirements are nuclear plants (15 percent).[436][yy] A much

[yy] These totals are based on announced retirements as of October 2016. Pending state action may prevent six nuclear reactors from retiring, and another reactor has since announced it will retire during this timeframe.

smaller percentage of planned retirements are diesel combustion and oil steam turbines. These are less prominent in planned retirements, in part because they now represent a much smaller percentage of the Nation's electricity capacity than has historically been the case.

During decommissioning, all plants have waste streams that need to be managed. Coal and nuclear power plants produce the largest amount of solid waste during generation. For coal plants, the most expensive part of decommissioning in many cases will be environmental remediation of the CCR disposal sites.[437] Nuclear waste is stored at the reactor site where it is generated. The lack of a centralized permanent waste disposal facility for nuclear waste means that spent fuel storage facilities require continued management after a plant has been decommissioned. Decommissioning needs will continue to evolve as new generators, especially non-hydro renewables, reach the end of their operating lives in the next 20–30 years. These plants have some unique waste streams, including large volumes of glass and aluminum, large fiberglass blades, and in some cases, rare earth metals; however, there is a high potential for recycling some of these materials, and wind plants often have the opportunity for repowering by upgrading the turbine.

3.4.8.1 Coal

Increases in coal retirements imply a greater need for decommissioning these plants. The coal ash byproduct of conventional coal-fired power plants is the largest quantity of solid waste produced from the generation of electricity.[438] The composition and quantity of this solid waste depends on the type of coal burned, the power conversion technology used, and the addition of environmental controls. Decommissioning needs include (1) data on waste and decommissioning costs; (2) development of coal plant decommissioning procedures; and (3) identification of barriers to waste recycling and options for overcoming these barriers.

3.4.8.2 Nuclear Power

NRC operating licenses for approximately 60 percent of the existing nuclear-power generating units in the United States will expire by 2040. Without further license extensions, these expirations could result in retirements and decommissioning wastes in the coming decades.[439] Nuclear plant owners must provide NRC with detailed decommissioning plans and periodic updates on the status of their decommissioning fund for the nuclear reactors they own.[440] Three of the paramount considerations when developing a decommissioning plan are the radiological contamination, condition, and configuration of the plant. Two decommissioning methods have been used in United States: Safe Enclosure ("SAFSTOR") and Immediate Dismantling ("DECON").[441] In DECON, the plant is immediately dismantled, and the site is prepped for reuse by removing nuclear waste in casks for storage. In SAFSTOR decommissioning, plant dismantling is deferred for about 50 years. There is currently no centralized permanent disposal facility for commercial used nuclear fuel in the United States, so this radioactive material is stored at reactor sites in 35 states awaiting construction of a permanent handling facility.[442]

3.4.8.3 Oil and Gas

Unlike coal plants and nuclear reactors, gas- and oil-fired plants do not generate combustion ash or nuclear waste. The unique solid waste concerns for gas- and oil-fired plants are the byproducts from emission controls. However, the solid waste from electricity generation is small because of the low adoption rate of these emission controls for gas- and oil-fired plants. These solid wastes are similar to the waste generated by environmental controls placed on the stacks of coal plants, especially for most post-combustion removal technology.

There are three methods for decommissioning an oil or gas plant, considering the conditions of the plants and the total budget: cold closure, selective demolition, or total demolition.[443] The decommissioning of gas and oil power plants creates construction and demolition waste, general refuse, and chemical waste.[444]

Chemical waste that is particular to oil and gas plants includes naturally occurring radioactive materials (NORM). During the oil and gas combustion process, because NORM are not volatile, burning away the carbon leads to higher levels of radioactive waste in scale, sludge, and scrapings of the generator, tanks, and pipelines.[445] Radioactive material can also form a thin film on the interior surfaces of gas processing equipment and vessels. Currently, no Federal regulations exist that specifically address the handling and disposal of NORM wastes. However, several oil-producing states (Texas, Louisiana, New Mexico, North Dakota, and Mississippi) have enacted specific NORM regulations.[446]

3.4.8.4 Hydropower

There are two options for decommissioning a hydropower plant. A partial retirement involves retirement of only the hydroelectric facilities and retains portions of the dam and other structures. Some rehabilitation of the structure for safety or maintenance may be required and can include reduction in height or breach of the dam. In this case, the dam is either reduced or eliminated, while some of the ancillary facilities may remain intact. A full retirement includes the removal of the project and all appurtenant structures, including rehabilitation or restoration of the affected project area. Decommissioning (whether partial or full) generally requires completion of an environmental impact statement, and every dam removal process will have site-specific engineering, environmental, and community issues.

3.4.8.5 Wind

To date, there have not been many wind decommissioning projects. As a result, details of decommissioning wind projects are very limited. In some states, developers are required to have decommissioning process and cost estimates ready with the decommissioning plan. In general, the decommissioning process of a wind plant consists of removing the turbine, destroying the concrete pads, restoring the surface, and replanting and rebuilding the soil of disturbed land. Communication towers are taken apart, removed, and then either disposed of, recycled or reused.[447]

3.4.8.6 Solar PV

Like wind, there have not been many decommissioning projects for solar to date. During decommissioning, PV modules must be removed from racks, and the racks must be dismantled. These are stored temporarily onsite until they are transferred by trucks to appropriate facilities, like recycling sites, or back to the manufacturer. Similarly, inverters and associated components must be transported to an appropriate site per local, state, and Federal waste disposal regulations. Finally, re-vegetation of the site is done to minimize erosion and disruption of vegetation. In the case of one solar farm decommissioning, the recycling value of the raw material for the solar array is expected to exceed the removal costs and provide a net economic benefit.[448]

While there is no industry-wide requirement for solar and wind developers to develop and fund decommissioning plans, BLM does impose decommissioning requirements on Federal lands. BLM requires developers seeking to site renewable generation projects on Federal lands to file a decommissioning plan and post a performance bond to help fund site remediation. The performance bond is intended to cover costs associated with (1) removing hazardous materials, including “herbicide use, petroleum-based fluids, and dust control or soil stabilization materials”; (2) decommissioning, removing, and properly disposing of all "surface facilities," such as panels; and (3) "addressing reclamation, revegetation, restoration, and soil stabilization," such as regrading or vegetation, as required under the Clean Water Act.[449] Thus, solar and wind facilities sited on Federal lands must have a decommissioning plan before they are granted right of way and must post a bond to fund decommissioning.

3.5 Endnotes

[1] Ian M. Hoffman, Gregory Rybka, Greg Leventis, Charles A. Goldman, Lisa Schwartz, Megan Billingsley, and Steven Schiller, *The Total Cost of Saving Electricity through Utility Customer-Funded Energy Efficiency Programs* (Berkeley, CA: Lawrence Berkeley National Laboratory, April 2015), 2, https://emp.lbl.gov/sites/all/files/total-cost-of-saved-energy.pdf. See also: Lazard, *Lazard's Levelized Cost of Energy Analysis—Version 9.0*. (Lazard, November 2015), 2, https://www.lazard.com/media/2390/lazards-levelized-cost-of-energy-analysis-90.pdf.

[2] Jocelyn Rogers, "New API Poll; Voters Want Candidates Who Support America's Energy Renaissance," American Petroleum Institute, June 21, 2016, http://www.api.org/~/media/Files/Policy/American-Energy/WhatAmericaIsThinking-Polling.pdf.

[3] Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Washington, DC: EPA, April 2016), EPA 430-R-16-002, Table ES-6, http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[4] Environmental Protection Agency (EPA), "Air Pollutant Emissions Trends Data: Average Annual Emissions," accessed December 19, 2016, https://www.epa.gov/sites/production/files/2015-07/national_tier1_caps.xlsx.

[5] The White House, *Economic Report of the President Together with the Annual Report of the Council of Economic Advisors* (Washington, DC: The White House, January 2017), https://www.whitehouse.gov/sites/default/files/docs/2017_economic_report_of_president.pdf.

[6] Energy Information Administration (EIA), *Annual Energy Outlook 2015 with Projections to 2040* (Washington, DC: EIA, 2015), DOE/EIA-0383(2015), http://www.eia.gov/outlooks/aeo/pdf/0383(2015).pdf.

[7] Energy Information Administration (EIA), *Annual Energy Outlook 2014 with Projections to 2040* (Washington, DC: EIA, 2015), DOE/EIA-0383(2014), MT-16, http://www.eia.gov/outlooks/aeo/pdf/0383(2014).pdf.

[8] Energy Information Administration (EIA), *Monthly Energy Review* (Washington, DC: EIA, December 2016), accessed December 16, 2016, Tables 2.1, 2.2, 2.3, 2.4, and 2.5, http://www.eia.gov/totalenergy/data/monthly.

[9] EPSA Analysis: Cara Marcy et al., "Electricity Generation Baseline Report," National Renewable Energy Laboratory, 2017.

[10] Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Washington, DC: EPA, April 2016), EPA 430-R-16-002, Table ES-6, http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[11] Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Washington, DC: EPA, April 2016), EPA 430-R-16-002, Table A-95–A-98, http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[12] Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Washington, DC: EPA, April 2016), EPA 430-R-16-002, Table 2-11, http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[13] Energy Information Administration (EIA), "Table 8.2. Average Tested Heat Rates by Prime Mover and Energy Source, 2007–2015 (Btu per Kilowatthour)," in *Electric Power Annual* (Washington, DC: EIA, 2016), www.eia.gov/electricity/annual/html/epa_08_02.html.

[14] "Carbon Dioxide Emissions Coefficients," Energy Information Administration, February 2, 2016, http://www.eia.gov/environment/emissions/co2_vol_mass.cfm.

[15] Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Washington, DC: EPA, April 2016), EPA 430-R-16-002, Table 2-12, http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[16] Energy Information Administration (EIA), *Monthly Energy Review* (Washington, DC: EIA, December 2015), DOE/EIA-00035(2015/12), Table 12.6, http://www.eia.gov/totalenergy/data/monthly/#electricity .

[17] Energy Information Administration (EIA), *Monthly Energy Review* (Washington, DC: EIA, 2016), accessed March 22, 2016, Tables 7.1 and 12.6, http://www.eia.gov/totalenergy/data/monthly.

[18] "International Data Base," U.S. Census Bureau, last updated August 2016, accessed March 22, 2016, http://www.census.gov/population/international/data/idb/informationGateway.php.

[19] "Gross Domestic Product," Department of Commerce, Bureau of Economic Analysis, accessed March 22, 2016, http://www.bea.gov/national/index.htm#gdp.

[20] EPSA Analysis: Caitlin Murphy and Colin Cunliff, "QER 1.2 Environment Baseline, Volume 1: Greenhouse Gas Emissions from the U.S. Power Sector," Department of Energy, 2017, Chapter 5, p. 65, Finding #6.

[21] Energy Information Administration (EIA), *Monthly Energy Review* (Washington, DC: EIA, 2016), accessed November 17, 2016, Table 12.1, http://www.eia.gov/totalenergy/data/monthly.

[22] Energy Information Administration (EIA), *Monthly Energy Review* (Washington, DC: EIA, 2016), accessed November 17, 2016, Tables 12.2–12.6, http://www.eia.gov/totalenergy/data/monthly.

[23] Alexander E. MacDonald, Christopher T. M. Clack, Anneliese Alexander, Adam Dunbar, James Wilczak, and Yuanfu Xie, "Future Cost-Competitive Electricity Systems and Their Impact on US CO_2 Emissions," *Nature Climate Change* 6 (2016): 526–31, doi:10.1038/nclimate2921.

[24] New York Independent System Operator (NYISO), *Power Trends 2016: The Changing Energy Landscape* (Rensselaer, NY: NYISO, 2016), http://www.nyiso.com/public/webdocs/media_room/publications_presentations/Power_Trends/Power_Trends/2016-power-trends-FINAL-070516.pdf.

[25] Intergovernmental Panel on Climate Change, *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (Cambridge, UK, and New York: Cambridge University Press, 2014), http://ipcc-wg2.gov/AR5/report.

[26] Energy Information Administration (EIA), *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016* (Washington, DC: EIA, 2016), 6, http://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[27] "Form EIA-923 detailed data," U.S. Energy Information Admnistration, accessed December 30, 2016, https://www.eia.gov/electricity/data/eia923/.

[28] Energy Information Administration (EIA), "Table 7.2b: Electric Power Sector," in *Monthly Energy Review* (Washington, DC: EIA, March 2016), DOE/EIA-0035(2016/3), 110, http://www.eia.gov/totalenergy/data/monthly/#electricity.

[29] EPSA Analysis: Caitlin Murphy and Colin Cunliff, "QER 1.2 Environment Baseline, Volume 1: Greenhouse Gas Emissions from the U.S. Power Sector," Department of Energy, 2017, 39.

[30] American Wind Energy Association (AWEA), *U.S. Wind Industry Fourth Quarter 2015 Market Report* (AWEA, 2016), 4, http://awea.files.cms-plus.com/FileDownloads/pdfs/4Q2015%20AWEA%20Market%20Report%20Public%20Version.pdf.

[31] Energy Information Administration (EIA), "Table 3.1.A. Net Generation by Energy Source: Total (all sectors)" and "Table "3.1.B. Net Generation from Renewable Sources: Total (all sectors)," in *Electric Power Annual* (Washington, DC: EIA, November 2016), https://www.eia.gov/electricity/annual.

[32] U.S. Energy Information Administration (EIA), "Table 4.2.A. Existing Net Summer Capacity by Energy Source and Producer Type" and "Table 4.2.B. Existing Net Summer Capacity of Other Renewable Sources by Producer Type," in *Electric Power Annual* (Washington, DC: EIA, November 2016), https://www.eia.gov/electricity/annual.

[33] April Lee and David Darling, "Wind Adds the Most Electric Generation Capacity in 2015, Followed by Natural Gas and Solar," Energy Information Administration, *Today in Energy,* March 23, 2016, http://www.eia.gov/todayinenergy/detail.php?id=25492.

[34] Energy Information Administration (EIA), "Table 4.2.B. Net Summer Capacity of Other Renewable Sources by Producer Type," in *Electric Power Annual* (Washington, DC: EIA, November 2016), https://www.eia.gov/electricity/annual.

[35] Julia Pyper, "The US Solar Market Is Now 1 Million Installations Strong," Greentech Media, April 21, 2016. https://www.greentechmedia.com/articles/read/The-U.S.-Solar-Market-Now-One-Million-Installations-Strong.

[36] Shayle Kann, M. J. Shiao, Cory Honeyman, Jade Jones, Austin Perea, Colin Smith, Benjamin Gallagher, et al., *U.S. Solar Market Insight 2015 Q4: Year in Review* (GTM Research and Solar Energy Industries Association, 2016), http://www.seia.org/sites/default/files/gMOip8F78iSMI2015YIR.pdf.

[37] U.S. Energy Information Administration (EIA), "Table 1.1A. Renewable Sources: Total –All Sectors, October 2016, "*Electric Power Monthly*," December 2016, http://www.eia.gov/electricity/monthly/.

[38] Energy Information Administration (EIA), "Table 6.2.B. Net Summer Capacity Using Primarily Renewable Energy Sources and by State, August 2016 and 2015 (Megawatts)," *Electric Power Monthly,* October 2016, http://www.eia.gov/electricity/monthly/.

[39] "Annual Technology Baseline and Standard Scenarios," National Renewable Energy Laboratory, last updated November 16, 2016, http://www.nrel.gov/analysis/data_tech_baseline.html.

[40] "SunShot Initiative 2030 Goals Paper and Graphics," Department of Energy, accessed December 19, 2016, https://energy.gov/eere/sunshot/downloads/sunshot-initiative-2030-goals-paper-and-graphics.

[41] Energy Information Administration (EIA), "Table 1.1: Net Generation by Energy Source: Total (All Sectors)," *Electric Power Monthly*, March 2016, http://www.eia.gov/electricity/monthly/.

[42] Energy Information Administration (EIA), "Table 7.6 Electricity End Use," *Monthly Energy Revie*w, November 2016, https://www.eia.gov/totalenergy/data/monthly.

[43] Department of Energy (DOE), *Wind Vision: A New Era for Wind Power in the United States* (Oak Ridge, TN: DOE, March 12, 2015), https://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf; R. Wiser, M. Bolinger, Galen L. Barbose, Naïm R. Darghouth, Ben Hoen, Andrew D. Mills, Joe Rand, et al., *2015 Wind Technologies Market Report* (Oak Ridge, TN: Department of Energy and Lawrence Berkeley National Laboratory, August 2016), DOE/GO-102016-4885, https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf.

[44] R. Wiser, M. Bolinger, Galen L. Barbose, Naïm R. Darghouth, Ben Hoen, Andrew D. Mills, Joe Rand, et al., *2015 Wind Technologies Market Report* (Oak Ridge, TN: Department of Energy and Lawrence Berkeley National Laboratory, August 2016), DOE/GO-102016-4885, https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf.

[45] Jose Zayas, Michael Derby, Patrick Gilman, Shreyas Ananthan, Eric Lantz, Jason Cotrell, Fredric Beck, and Richard Tusing, *Enable Wind Power Nationwide*, edited by Elizabeth Hartman and Coryne Tasca (Department of Energy, Office of Energy Efficiency and Renewable Energy, 2015), DOE/EE-1218, http://energy.gov/sites/prod/files/2015/05/f22/Enabling%20Wind%20Power%20Nationwide_18MAY2015_FINAL.pdf.

[46] Trieu Mai, Wesley Cole, Eric Lantz, Cara Marcy, and Benjamin Sigrin*, Impacts of Federal Tax Credit Extensions on Renewable Deployment and Power Sector Emissions* (Golden, CO: National Renewable Energy Laboratory, 2016), NREL/TP-6A20-65571, 18–21, Figure 6, http://www.nrel.gov/docs/fy16osti/65571.pdf.

[47] Steve Capanna, "New Study: Renewable Energy for State Renewable Portfolio Standards Yield Sizable Benefits," Department of Energy, Office of Energy Efficiency and Renewable Energy, January 7, 2016, http://energy.gov/eere/articles/new-study-renewable-energy-state-renewable-portfolio-standards-yield-sizable-benefits.

[48] Galen Barbose, *U.S. Renewables Portfolio Standards: 2016 Annual Status Report* (Lawrence Berkeley National Laboratory, 2016), LBNL-1005057, https://emp.lbl.gov/sites/all/files/lbnl-1005057.pdf.

[49] Database of State Incentives for Renewables & Efficiency® (DSIRE), "Renewable Portfolio Standard Policies," NC Clean Energy Technology Center, August 2016, http://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2014/11/Renewable-Portfolio-Standards.pdf.

[50] Ryan Wiser, Trieu Mai, Alberta Carpenter, David Keyser, and Andrew Mills, *A Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards* (Lawrence Berkley National Laboratory and National Renewable Energy Laboratory, 2016), TP-6A20-65005, 12, https://emp.lbl.gov/sites/all/files/lbnl-1003961.pdf.

[51] Galen Barbose, "RPS Compliance Summary Data," Lawrence Berkley National Laboratory, last updated February 1, 2016, https://emp.lbl.gov/sites/all/files/RPS%20Compliance%20Data_Feb%202016.xlsx.

[52] Eric O'Shaughnessy, Chang Liu, and Jenny Heeter, *Status and Trends in the U.S. Voluntary Green Power Market (2015 Data)*, (Golden, CO: National Renewable Energy Lab, 2016), NREL/TP-6A20-67147, http://www.nrel.gov/docs/fy17osti/67147.pdf.

[53] Ryan Wiser, Trieu Mai, Alberta Carpenter, David Keyser, and Andrew Mills, *A Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards* (Lawrence Berkley National Laboratory and National Renewable Energy Laboratory, 2016), TP-6A20-65005, http://www.nrel.gov/docs/fy16osti/65005.pdf.

[54] Ryan Wiser, Trieu Mai, Alberta Carpenter, David Keyser, and Andrew Mills, *A Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards* (Lawrence Berkley National Laboratory and National Renewable Energy Laboratory, 2016), TP-6A20-65005, http://www.nrel.gov/docs/fy16osti/65005.pdf.

[55] Jonathan Glicoes, "Renewable Portfolio Standards: An Analysis of Net Job Impacts" (master's thesis, Georgetown University, 2013), https://repository.library.georgetown.edu/handle/10822/559510.

[56] Ryan Wiser, Trieu Mai, Alberta Carpenter, David Keyser, and Andrew Mills, *A Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards* (Lawrence Berkley National Laboratory and National Renewable Energy Laboratory, 2016), TP-6A20-65005, http://www.nrel.gov/docs/fy16osti/65005.pdf.

[57] Ellis, Abraham, R. Nelson, E. Von Engeln, R. Walling, J. MacDowell, L. Casey, E. Seymour, et al. 2012. "Reactive Power Performance Requirements for Wind and Solar Plants." In Power and Energy Society General Meeting, 2012 IEEE, 1–8. IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6345568.

[58] Nelson, Robert. 2011. "Active Power Control in Siemens Wind Turbines." http://www.nrel.gov/electricity/transmission/pdfs/nelson.pdf.

[59] Nelson, R. J., H. Ma, and N. M. Goldenbaum. 2011. "Fault Ride-through Capabilities of Siemens Full-Converter Wind Turbines." In Power and Energy Society General Meeting, 2011 IEEE, 1–5. IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6039729.

[60] National Renewable Energy Laboratory (NREL). 2014. "Advanced Inverter Functions to Support High Levels of Distributed Solar: Policy and Regulatory Considerations." http://www.nrel.gov/docs/fy15osti/62612.pdf.

[61] Department of Energy (DOE). 2015. "Global Energy Storage Database." US Department of Energy (DOE), Sandia National Laboratory, October.

[62] Muljadi, Eduard, Vahan Gevorgian, Mohit Singh, and Surya Santoso. 2012. "Understanding Inertial and Frequency Response of Wind Power Plants." IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6316361.

[63] Gonzalez-Longatt, Francisco M. 2015. "Activation Schemes of Synthetic Inertia Controller for Full Converter Wind Turbine Generators." In PowerTech, 2015 IEEE Eindhoven, 1–5. IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7232292.

[64] Erdal Kara, "Renewable integration and direction of US electricity markets," Energy Central, December 30, 2015, http://www.energycentral.com/c/um/renewable-integration-and-direction-us-electricity-markets, accessed December 13, 2016.

[65] Energy Information Administration (EIA), *Short-Term Energy Outlook*, (Washington, DC: EIA, December 6, 2016), Table 7d, http://www.eia.gov/outlooks/steo/tables/pdf/7dtab.pdf.

[66] Energy Information Administration (EIA), *Short-Term Energy Outlook*, (Washington, DC: EIA, December 6, 2016), Table 7d, http://www.eia.gov/outlooks/steo/tables/pdf/7dtab.pdf.

[67] Energy Information Administration (EIA), *U.S. Energy-Related Carbon Dioxide Emissions, 2014* (Washington, DC: EIA, 2015), 12, http://www.eia.gov/environment/emissions/carbon/pdf/2014_co2analysis.pdf.

[68] Timothy Skone, James Littlefield, Joe Marriott, Greg Cooney, Matt Jamieson, Jeremie Hakian, and Greg Schivley, *Life Cycle Analysis of Natural Gas Extraction and Power Generation* (National Energy Technology Laboratory, 2014), DOE/NETL-2014/1646, https://www.netl.doe.gov/energy-analyses/temp/NaturalGasandPowerLCAModelDocumentationNG%20Report_052914.pdf.

[69] Energy Information Administration (EIA), "Table 7.2a. Electricity Net Generation: Total (All Sectors)," *Monthly Energy Review*, November 2016, http://www.eia.gov/totalenergy/data/monthly.

[70] EPSA Analysis: Cara Marcy et al., "Electricity Generation Baseline Report," National Renewable Energy Laboratory, 2017.

[71] Jaime López, Wärtsilä, "Combustion Engine Vs Gas Turbine: Ramp Rate," Wärtsilä, accessed December 15, 2016, http://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-vs-gas-turbine-ramp-rate.

[72] IEA Environmental Projects Ltd, *Operating Flexibility of Power Plants with CCS*, (Chektenham, United Kingdon: IEA Environmental Projects Ltd, June 2012), 14, http://hub.globalccsinstitute.com/sites/default/files/publications/104631/operating-flexibility-power-plants-ccs.pdf.

[73] EPSA Analysis: Cara Marcy et al., "Electricity Generation Baseline Report," National Renewable Energy Laboratory, 2017.

[74] EPSA Analysis: Cara Marcy et al., "Electricity Generation Baseline Report," National Renewable Energy Laboratory, 2017.

[75] Energy Information Administration (EIA), "Table 6.7A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels" and Table 6.7B. Capacity Factors for Utility Scale Generators Not Primarily Using Fossil Fuels," *Electric Power Monthly,* April 2016, http://www.eia.gov/electricity/monthly/.

[76] Elena Verdolini, Francesco Vona, David Popp, "Bridging the Gap: Do Fast Reacting Fossil Technologies Facilitate Renewable Energy Diffusion?" working paper 22454 (Cambridge, MA: National Bureau of Economic Research, July 2016), http://www.nber.org/papers/w22454.

[77] FERC, FERC Open Access Podcast Transcript, Winter Assesment Presented by FERC Staff, October 27, 2016 https://www.ferc.gov/media/podcast/2016/10-27-transcript.pdf, accessed December 13, 2016.

[78] United Nations Economic Commission for Europe, *From Source to Use: The Role of Fossil Fuels in Delivering a Sustainable Energy Future* (Geneva, Switzerland: United Nations ECE, 2014), ECE/ENERGY/2014/5/Rev.1, 3, http://www.unece.org/fileadmin/DAM/energy/se/pdfs/comm23/ECE.ENERGY.2014.5_e.pdf.

[79] National Coal Council, *Leveling the Playing Field: Policy Parity for Carbon Capture and Storage Technologies* (Washington, DC: National Coal Council, 2015), 2, http://www.nationalcoalcouncil.org/studies/2015/Leveling-the-Playing-Field-for-Low-Carbon-Coal-Fall-2015.pdf.

[80] R. Uria-Martinez, P. O'Connor, and M. Johnson, *2014 Hydropower Market Report* (Washington, DC: Department of Energy, 2015), DOE/EE 1195, https://www.energy.gov/eere/water/downloads/2014-hydropower-market-report.

[81] Shih-Chieh Kao, Ryan A. McManamay, Kevin M. Stewart, Nicole M. Samu, Boualem Hadjerioua, Scott T. DeNeale, Dilruba Yeasmin, et al. *New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States* (Washington. DC: Department of Energy, April 2014), 17, https://nhaap.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf.

[82] Boualem Hadjerioua, Yaxing Wei, and Shih-Chieh Kao, "An Assessment of Energy Potential at Non-Powered Dams in the United States." U.S. Department of Energy. http://nhaap.ornl.gov/sites/default/files/NHAAP_NPD_FY11_Final_Report.pdf.

[83] Department of Energy (DOE), *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source* (Oak Ridge, TN: DOE, 2016), https://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-10262016_0.pdf.

[84] U.S. Energy Information Administration (EIA), "Table 7.2b: Electricity Net Generation: Electric Power Sector" in Monthly Energy Review (Washington, DC: EIA, December 2015), DOE/EIA-00035(2015/12), 107 and 181, http://www.eia.gov/totalenergy/data/monthly/#electricity.

[85] Shih-Chieh Kao, Ryan A. McManamay, Kevin M. Stewart, Nicole M. Samu, Boualem Hadjerioua, Scott T. DeNeale, Dilruba Yeasmin, et al. *New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States* (Washington. DC: Department of Energy, April 2014), 17, https://nhaap.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf.

[86] Energy Information Administration (EIA), *Monthly Update to Annual Electric Generator Report* (Washington, DC: EIA, 2016), DOE/EIA-860m(2016), https://www.eia.gov/electricity/data/eia860m/.

[87] Energy Information Administration (EIA), *EIA 860M* (EIA, August 2016), https://www.eia.gov/electricity/data/eia860m/.

[88] R. Uria-Martinez, P. O'Connor, and M. Johnson, 2014 Hydropower Market Report (Washington, DC: Department of Energy, 2015), DOE/EE 1195, http://energy.gov/sites/prod/files/2015/05/f22/2014%20Hydropower%20Market%20Report_20150512_rev6.pdf.

[89] Department of Energy (DOE), *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source* (Oak Ridge, TN: DOE, 2016), DOE/GO-102016-4869, https://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-10262016_0.pdf.

[90] Department of Energy (DOE), *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source* (Oak Ridge, TN: DOE, 2016), DOE/GO-102016-4869, https://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-10262016_0.pdf.

[91] EPSA Analysis: Cara Marcy et al., "Electricity Generation Baseline Report," National Renewable Energy Laboratory, forthcoming.

[92] Fred Mayes, "Southern States Lead Growth in Biomass Electricity Generation," Energy Information Administration, *Today in Energy*, May 25, 2016, https://www.eia.gov/todayinenergy/detail.php?id=26392.

[93] "Electricity Data Browser," Energy Information Administration, accessed December 16, 2016, http://www.eia.gov/electricity/data/browser.

[94] "Frequently Asked Questions: What is U.S. Electricity Generation by Energy Source?" Energy Information Administration, accessed December 16, 2016, https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3.

[95] B. Matek, *The Values of Geothermal Energy: A Discussion of the Benefits Geothermal Power Provides to the Future U.S. Power System* (Washington, DC: Geothermal Energy Association, October 2013), http://geo-energy.org/reports/Values%20of%20Geothermal%20Energy%20Draft%20Final.pdf.

[96] Energy Information Administration (EIA), "Net Generation by Sectors," *Electric Power Monthly*, accessed December 12, 2016, http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01.

[97] QER Analysis: Kristy Harmon and Daniel Shea., "State Options to Keep Nuclear Energy in the Mix," National Conference of State Legislatures, January 2017.

[98] "Status of License Renewal Applications and Industry Activities," Nuclear Regulatory Commission, last updated December 2, 2016, http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html.

[99] "Status of License Renewal Applications and Industry Activities," Nuclear Regulatory Commission, last updated December 2, 2016, http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html.

[100] "Status of License Renewal Applications and Industry Activities," Nuclear Regulatory Commission, last updated December 2, 2016, http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html.

[101] "Status of License Renewal Applications and Industry Activities," Nuclear Regulatory Commission, last updated December 2, 2016, http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html.

[102] "Combined License Holder for New Reactors," Nuclear Regulatory Commission, last updated February 24, 2016, https://www.nrc.gov/reactors/new-reactors/col-holder.html.

[103] Whitney Herndon and John Larsen, "Nukes in the Crosshairs Revisited: The Market and Emissions Impacts of Retirements," Rhodium Group, LLC, November 4, 2016, http://rhg.com/notes/nukes-in-the-crosshairs-revisited.

[104] Julien Dumoulin-Smith and Jerimiah Booream, *US Electric Utilities & IPP's: Can ZECs Succeed? Mining the Legal Road Ahead (Incl. Transcript)* (UBS, Securities LLC, 2016), https://neo.ubs.com/shared/d1HXDeiWjftpeuF/.

[105] Secretary of Energy Advisory Board Task Force on the Future of Nuclear Power, *Report of the Task Force on the Future of Nuclear Power* (Washington, DC: Department of Energy, September 22, 2016), http://www.energy.gov/seab/downloads/final-report-task-force-future-nuclear-power.

[106] Whitney Herndon and John Larsen, "Nukes in the Crosshairs Revisited: The Market and Emissions Impacts of Retirements," Rhodium Group, LLC, November 4, 2016, http://rhg.com/notes/nukes-in-the-crosshairs-revisited.

[107] Ronaldo Szilard, Phil Sharpe, Edward Kee, Edward Davis, and Eugene Grecheck, *Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet* (Energy Systems Strategic Assessment Institute, 2016), INL/EXT-16-39951, https://gain.inl.gov/Shared%20Documents/Economics-Nuclear-Fleet.pdf.

[108] Illinois (IL) Commerce Commission, IL Power Agency, IL Environmental Protection Agency, IL Department of Commerce and Economic Opportunity, *Potential Nuclear Power Plant Closings in Illinois- Impacts and Market-Based Solutions*, report prepared in response to IL General Assembly House Resolution 1146, (Springfield, IL: IL Commerce Commission, IL Power Agency, IL Environmental Protection Agency, IL Department of Commerce and Economic Opportunity, 2015), http://www.illinois.gov/sites/ipa/Documents/HR1146-Report.pdf

[109] Whitney Herndon and John Larsen, "Nukes in the Crosshairs Revisited: The Market and Emissions Impacts of Retirements," Rhodium Group, LLC, November 4, 2016, http://rhg.com/notes/nukes-in-the-crosshairs-revisited.

[110] R. G. Pratt, P. J. Balducci, C. Gerkensmeyer, S. Katipamula, M. C. W. Kintner-Meyer, T. F. Sanquist, K. P. Schneider, and T. J. Secrest, *The Smart Grid: An Estimation of the Energy and CO_2 Benefits* (Richland, WA: Pacific Northwest National Laboratory, 2010), PNNL-19112, Revision 1, http://energyenvironment.pnnl.gov/news/pdf/PNNL-19112_Revision_1_Final.pdf.

[111] R. G. Pratt, P. J. Balducci, C. Gerkensmeyer, S. Katipamula, M. C. W. Kintner-Meyer, T. F. Sanquist, K. P. Schneider, and T. J. Secrest, *The Smart Grid: An Estimation of the Energy and CO_2 Benefits* (Richland, WA: Pacific Northwest National Laboratory, 2010), PNNL-19112, Revision 1, http://energyenvironment.pnnl.gov/news/pdf/PNNL-19112_Revision_1_Final.pdf.

[112] "Appliance and Equipment Standards Program," Department of Energy, Office of Energy Efficiency and Renewable Energy, accessed April 25, 2016, http://energy.gov/eere/buildings/appliance-and-equipment-standards-program.

[113] Department of Energy (DOE), Building Technologies Office (BTO), *Appliance and Equipment Standards Fact Sheet*, (Washington, DC: DOE-BTO, October 2016), DOE/EE-1086, http://energy.gov/eere/buildings/downloads/appliance-and-equipment-standards-fact-sheet.

[114] Department of Energy (DOE), Building Technologies Office (BTO), *Appliance and Equipment Standards Fact Sheet*, (Washington, DC: DOE-BTO, October 2016), DOE/EE-1086, http://energy.gov/eere/buildings/downloads/appliance-and-equipment-standards-fact-sheet.

[115] Department of Energy (DOE), Building Technologies Office (BTO), *Appliance and Equipment Standards Fact Sheet*, (Washington, DC: DOE-BTO, October 2016), DOE/EE-1086, 1, http://energy.gov/eere/buildings/downloads/appliance-and-equipment-standards-fact-sheet.

[116] Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards for Small, Large, and Very Large Air-Cooled Commercial Package Air Conditioning and Heating Equipment and Commercial Warm Air Furnaces: Correction, 81 Fed. Reg. 53907, 10 C.F.R. § 431 (August, 15, 2016).

[117] Department of Energy (DOE), Building Technologies Office (BTO), *Appliance and Equipment Standards Fact Sheet*, (Washington, DC: DOE-BTO, October 2016), DOE/EE-1086, 1, http://energy.gov/eere/buildings/downloads/appliance-and-equipment-standards-fact-sheet.

[118] "About ENERGY STAR: History and Accomplishments," Environmental Protection Agency, accessed December 15, 2016, https://www.energystar.gov/about/history.

[119] Department of Energy (DOE), *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities* (Washington, DC: DOE, 2015), 144, https://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf.

[120] "The Impact of Building Energy Codes," Department of Energy, Building Energy Codes Program, last updated November 21, 2016, https://www.energycodes.gov/about/results.

[121] Department of Energy (DOE), *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities* (Washington, DC: DOE, 2015), 146, https://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf.

[122] Department of Energy (DOE), *DOE Zero Energy Ready Home Savings and Cost Estimate Summary* (DOE, 2015), 4, http://energy.gov/eere/buildings/downloads/doe-zero-energy-ready-home-savings-and-cost-estimate-summary.

[123] Environmental Protection Agency, *Your ENERGY STAR Certified New Home: Better is Better,* Consumer Brochure (EPA, 2012), 9, https://www.energystar.gov/ia/partners/downloads/consumer_brochure.pdf.

[124] Department of Energy (DOE), *DOE Zero Energy Ready Home Savings and Cost Estimate Summary* (DOE, 2015), 4, http://energy.gov/eere/buildings/downloads/doe-zero-energy-ready-home-savings-and-cost-estimate-summary.

[125] Environmental Protection Agency (EPA), *Cost and Savings Benefits, ENERGY STAR Certified Homes, Version 3* (EPA, 2016), 4, https://www.energystar.gov/ia/partners/bldrs_lenders_raters/downloads/EstimatedCostandSavings.pdf?f05c-fe07.

[126] Joshua Kneifel, *Life-Cycle Cost Comparison of the NIST Net Zero Energy Residential Test Facility to a Maryland Code-Compliant Design* (National Institute of Standards and Technology, May 2014), NIST Special Publication 1172, iii, http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1172.pdf.

[127] Amy Cortese, Cathy Higgins, et al., *2014 Getting to Zero Status Update: A look at the projects, policies and programs driving zero net energy performance in commercial buildings*, (Vancouver, WA: New Buildings Institute, 2014), 4, 21, http://newbuildings.org/sites/default/files/2014_Getting_to_Zero_Update.pdf.

[128] Joshua Kneifel, *Life-Cycle Cost Comparison of the NIST Net Zero Energy Residential Test Facility to a Maryland Code-Compliant Design* (National Institute of Standards and Technology, May 2014), NIST Special Publication 1172, iii, http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1172.pdf.

[129] Environmental Protection Agency. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014." Table 2-12. April 2016. http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[130] Combined Heat and Power (CHP) Technical Potential in the United States, (Washington, DC: U.S. Department of Energy, 2016), iii, DOE/EE-1328, http://www.energy.gov/sites/prod/files/2016/04/f30/CHP%20Technical%20Potential%20Study%203-31-2016%20Final.pdf.

[131] Department of Energy (DOE), Combined Heat and Power (CHP) Technical Potential in the United States, (Washington, DC: DOE, 2016), 12, 17, DOE/EE-1328, http://www.energy.gov/sites/prod/files/2016/04/f30/CHP%20Technical%20Potential%20Study%203-31-2016%20Final.pdf.

[132] P. Cappers, J. MacDonald, and C. Goldman, Market and Policy Barriers for Demand Response Providing Ancillary Services in U.S. Markets (Berkeley, CA: Lawrence Berkeley National Laboratory, 2013), LBNL-6155E, https://emp.lbl.gov/publications/market-and-policy-barriers-demand.

[133] EnerNOC and the Brattle Group, The Role of Demand Response in Integrating Variable Energy Resources, Final Report, (Western Energy Board, December 2013), http://www.westernenergyboard.org/sptsc/documents/12-20-13SPSC_EnerNOC.pdf

[134] J. H. Williams, A. DeBenedictis, R. Ghanadan, A. Mahone, J. Moore, W. R. Morrow III, S. Price, and M. S. Tom, "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity," *Science* 335, no. 6064 (2012): 53–9, doi:10.1126/science.1208365.

[135] Peter J. Loftus, Armond M. Cohen, Jane C. S. Long, and Jesse D. Jenkins, "A Critical Review of Global Decarbonization Scenarios: What Do They Tell Us about Feasibility?" *WIREs Climate Change* 6, no. 1 (2015): 93–112, doi:10.1002/wcc.324.

[136] The White House, *United States Mid-Century Strategy for Deep Decarbonization* (Washington, DC: The White House, 2016), 8, 17, https://www.whitehouse.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf.

[137]Jae Edmonds, Leon Clarke, Marshall Wise, Hugh Pitcher, and Steve Smith, "Implications for the USA of Stabilization of Radiative Forcing at 3.4 W/m2," *Climate Policy* 8, sup. 1 (2008): S76–92, doi:10.3763/cpol.2007.0495.

[138] James H. Williams, Benjamin Haley, Fredrich Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, and Haewon McJeon, *Pathways to Deep Decarbonization in the United States,* revision with technical supplement (San Francisco, CA: Energy and Environmental Economics, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, November 2015), 19, 42, http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Technical_Report.pdf.

[139] James H. Williams, Benjamin Haley, and Ryan Jones, *Policy Implications of Deep Decarbonization in the United States* (San Francisco, CA: Energy Environmental Economics, Inc., 2015), US 2050 Report, Volume 2, 22, 41, 91, http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Policy_Report.pdf.

[140] David McCollum, Christopher Yang, Sonia Yeh, and Joan Ogden, "Deep Greenhouse Gas Reduction Scenarios for California – Strategic Implications from the CA-TIMES Energy-Economic Systems Model," *Energy Strategy Reviews* 1, no. 1 (2012): 19–32, doi:10.1016/j.esr.2011.12.003.

[141] Max Wei, James H. Nelson, Jeffery B. Greenblatt, Ana Mileva, Josiah Johnston, Michael Ting, Christopher Yang, Chris Jones, James E. McMahon, and Daniel M. Kammen, "Deep Carbon Reductions in California Require Electrification and Integration across Economic Sectors," *Environmental Research Letters* 8 (2013): 014038, doi:10.1088/1748-9326/8/1/014038.

[142] Owen Comstock, "Everywhere but Northeast, Fewer Homes Choose Natural Gas as Heating Fuel," Energy Information Administration*, Today in Energy*, September 25, 2014, http://www.eia.gov/todayinenergy/detail.cfm?id=18131.

[143] Eric Wilson, Craig Christensen, Scott Horowitz, Joseph Robertson, and Jeff Maguire, *Electric End Use Energy Efficiency Potential in the U.S. Single-Family Housing Stock* (Golden, CO: National Renewable Energy Laboratory, January 2017).

[144] Owen Comstock, "Everywhere but Northeast, Fewer Homes Choose Natural Gas as Heating Fuel," Energy Information Administration*, Today in Energy*, September 25, 2014, http://www.eia.gov/todayinenergy/detail.cfm?id=18131

[145] Eric Wilson, Craig Christensen, Scott Horowitz, Joseph Robertson, and Jeff Maguire, *Electric End Use Energy Efficiency Potential in the U.S. Single-Family Housing Stock* (Golden, CO: National Renewable Energy Laboratory, January 2017).

[146] "eGRID2012," Environmental Protection Agency, last updated October 8, 2015, https://www.epa.gov/energy/egrid.

[147] Eric Wilson, Craig Christensen, Scott Horowitz, Joseph Robertson, and Jeff Maguire, *Electric End Use Energy Efficiency Potential in the U.S. Single-Family Housing Stock* (Golden, CO: National Renewable Energy Laboratory, January 2017).

[148] James H. Williams, Benjamin Haley, Fredrich Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, and Haewon McJeon, *Pathways to Deep Decarbonization in the United States,* revision with technical supplement (San Francisco, CA: Energy and Environmental Economics, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, November 2015), Table 7, http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Technical_Report.pdf.

[149] Electric Power Research Institute (EPRI), *Electrotechnology Reference Guide: Revision 4* (EPRI, 2012), http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001025038.

[150] Vanessa J. Schweizer and M. Granger Morgan, "Bounding US Electricity Demand in 2050," *Technological Forecasting and Social Change* 105 (2016): 215–23, doi:10.1016/j.techfore.2015.09.001.

[151] WSP and Parsons Brinckerhoff and DNV GL, *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Glass* (Department of Energy and Climate Change and the Department for Business, Innovation and Skills, March 2015), https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416675/Glass_Report.pdf.

[152] Martin Wōrtler, Felix Schuler, Nicole Voigt, Torben Schmidt, Peter Dahlmann, Hans Bodo Lüngen, and Jean-Theo Ghenda, *Steel's Contribution to a Low-Carbon Europe 2050* (Boston, MA: Boston Consulting Group, Steel Institute VDEh, 2013), http://www.stahl-online.de/wp-content/uploads/2013/09/Schlussbericht-Studie-Low-carbon-Europe-2050_-Mai-20131.pdf.

[153] WSP and Parsons Brinckerhoff and DNV GL, *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Glass* (Department of Energy and Climate Change and the Department for Business, Innovation and Skills, March 2015), https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416675/Glass_Report.pdf.

[154] Stefan Wolf, "Industrial Heat Pumps in Germany – Potentials, Technological Development and Application Examples" (paper presented at the Achema Congress 2012, Frankfurt, Germany, June 13, 2012), http://web.ornl.gov/sci/usnt/03InHPsAchmaIERWolf.pdf.

[155] WSP and Parsons Brinckerhoff and DNV GL, *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Glass* (Department of Energy and Climate Change and the Department for Business, Innovation and Skills, March 2015), https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416675/Glass_Report.pdf.

[156] The White House, *United States Mid-Century Strategy for Deep Decarbonization* (Washington, DC: The White House, 2016), 8, 17, https://www.whitehouse.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf.

[157] Marco Miotti, Geoffrey J. Supran, Ella J. Kim, and Jessika E. Trancik, "Personal Vehicles Evaluated against Climate Change Mitigation Targets," *Environmental Science & Technology* 50, no. 20 (2016): 10795–804, doi:10.1021/acs.est.6b00177.

[158] Williams, James H., Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow III, Snuller Price, and Margaret S. Torn, "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity." *Science* 335, no. 6064 (2012): 53, doi:10.1126/science.1208365.

[159] Environmental Protection Agency (EPA), *U.S. Greenhouse Gas Inventory Report: 1990-2014* (Washington, DC: EPA, 2016), Tables A 95–98, https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.

[160]"Fact 936 : Aust 1, 2016 California had the highest concentration of Plug-in Vehicles Relative to Population in 2015," U.S. Department of Energy, accessed December 30, 2016, http://energy.gov/eere/vehicles/fact-936-august-1-2016-california-had-highest-concentration-plug-vehicles-relative,.

[161] David L. Greene and Shuguang Ji, "Policies for Promoting Low-Emission Vehicles and Fuels: Lessons from Recent Analysis" (Knoxville, TN: The Howard H. Baker Jr. Center for Public Policy, 2016), 4.

[162] Gloria Helfand and Ann Wolverton, "Evaluating the Consumer Response to Fuel Economy: A Review of the Literature," working paper #09-04 (Washington, DC: U.S. Environmental Protection Agency National Center for Environmental Economics, 2009), https://www.epa.gov/sites/production/files/2014-12/documents/evaluating_the_consumer_response_to_fuel_economy.pdf.

[163] David L. Greene and Shuguang Ji, "Policies for Promoting Low-Emission Vehicles and Fuels: Lessons from Recent Analysis" (Knoxville, TN: The Howard H. Baker Jr. Center for Public Policy, 2016), 33.

[164] L. Schwartz, et al., *Electricity End Use, Energy Efficiency, and Distributed Energy Resources Baseline* (Lawrence Berkeley National Laboratory, 2017), 196.

[165] "Common Concerns about Electric Vehicle Policy and Electric Vehicles," Center for Climate and Energy Solutions, accessed December 12, 2016, http://www.c2es.org/pev-action-tool/common-concerns-issue-brief.

[166] Dominic Hofstetter, "EVs and Total Cost of Ownership: Should Consumers Pay Upfront Today for Electrons Tomorrow?" Greentech Media, October 26, 2011, https://www.greentechmedia.com/articles/read/total-cost-of-ownership.

[167] "Alternative Fuels Data Center: Vehicle Cost Calculator," Department of Energy, last updated May 3, 2016, http://www.afdc.energy.gov/calc/.

[168] Luke Bassett, James Brodrick, Steve Capanna, Jonathan Castellano, Christy Cooper, Paul Donohoo-Vallett, David Feldman, Roland Gravel, Jason Hartke, David Howell, Amy Jiron, Tarak Shah, Gurpreet Singh, Carol Schutte, Rich Tusing, Jacob Ward, *Revolution…Now: The Future Arrives for Five Clean Energy Technologies – 2015 Update* (Washington, DC: U.S. Department of Energy, 2015), 15, http://www.energy.gov/sites/prod/files/2015/11/f27/Revolution-Now-11132015.pdf.

[169] A. Elgowainy, J. Han, J. Ward, F. Joseck, D. Gohlke, A. Lindauer, T. Ramsden, M. Biddy, M. Alexander, S. Barnhart, I. Sutherland, L. Verduzco, and T. J. Wallington, *Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies* (Argonne, IL: Argonne National Laboratory, 2016), ANL-ESD-16/7, 67.

170 Severin Borenstein and Lucas W. Davis, *The Distributional Effects of U.S. Clean Energy Tax Credits* (Cambridge, MA: National Bureau of Economic Research, 2015), Working Paper 21437, http://www.nber.org/papers/w21437.

171 "Income Eligibility," California Vehicle Rebate Project, last updated March 29, 2016, https://cleanvehiclerebate.org/eng/income-eligibility.

172 Tamara L. Sheldon, J. R. DeShazo, and Richard T. Carson, "Designing Policy Incentives for Cleaner Technologies: Lessons from California's Plug-In Electric Vehicle Rebate Program," in *Transportation Research Board 94th Annual Meeting Compendium of Papers* (Washington, DC: Transportation Research Board, 2015), http://energy.umich.edu/sites/default/files/DeShazo%20Carson%20Sheldon%20Paper%202014.10.02.pdf.

173 Severin Borenstein and Lucas Davis, *The Distributional Effects of U.S. Clean Energy Tax Credits* (Cambridge, MA: National Bureau of Economic Research, July, 2015), Working Paper 21437, 14, http://www.nber.org/papers/w21437.pdf.

174 California Air Resource Board, *Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses (Draft)* (Sacramento, CA: California Air Resources Board, 2015), https://www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf.

175 California Air Resource Board, *Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses (Draft)* (Sacramento, CA: California Air Resources Board, 2015), https://www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf.

176 Margaret Smith and Jonathan Castellano, C*osts Associated With Non-Residential Electric Vehicle Supply Equipment* (Department of Energy Vehicle Technologies Office, November 2015), http://www.afdc.energy.gov/uploads/publication/evse_cost_report_2015.pdf; The EV Project, *What Were the Cost Drivers for the Direct Current Fast Charging Installations?* (Idaho National Laboratory, March 2015), INL/MIS-15-35060, https://avt.inl.gov/sites/default/files/pdf/EVProj/WhatWereTheCostDriversForDCFCinstallations.pdf.

177 "Electric Vehicle Charging Station Locations," Department of Energy, last updated June 17, 2015, http://www.afdc.energy.gov/fuels/electricity_locations.html.

178 David L. Greene and Shuguang Ji, "Policies for Promoting Low-Emission Vehicles and Fuels: Lessons from Recent Analysis" (Knoxville, TN: The Howard H. Baker Jr. Center for Public Policy, 2016), 26.

179 Yan Zhou, Todd Levin, and Steven E. Plotkin, *Plug-in Electric Vehicle Policy Effectiveness: Literature Review* (Argonne, IL: Argonne National Laboratory, 2016), ANL/ESD-16/8.

180 Lisa Jerram, Will Sierzchula, Scott Robinson, and John Gartner, *DC Charging Map for the United States* (Boulder, CO: Navigant Research, 2Q 2016), 4.

181 Paul Menser, "Charging Behavior Revealed," Idaho National Laboratory, accessed October 27, 2016, https://www.inl.gov/article/charging-behavior-revealed-large-national-studies-analyze-ev-infrastructure-needs/.

182 Department of Energy (DOE), *U.S. Department of Energy's EV Everywhere Workplace Charging Challenge Mid-Program Review: Employees Plug In* (Washington, DC: DOE 2015), DOE/GO-102015-4836, http://energy.gov/sites/prod/files/2015/12/f27/105313-5400-BR-0-EERE%20Charging%20Challenge-FINAL_0.pdf.

183 "Alternative Fuels Data Center, Federal and State Laws and Incentives," Department of Energy, accessed October 14, 2016, http://www.afdc.energy.gov/laws/.

184 "Federal Highway Administration Unveils National 'Alternative Fuel and Electric Charging' Network," Department of Transportation, November 3, 2016, https://www.fhwa.dot.gov/pressroom/fhwa1656.cfm.

185 "Federal Highway Administration Unveils National 'Alternative Fuel and Electric Charging' Network," Department of Transportation, November 3, 2016, https://www.fhwa.dot.gov/pressroom/fhwa1656.cfm.

186 "U.S. Light-Duty Zero Emission Vehicle (ZEV) Sales (2011–2016)," Alliance of Automobile Manufacturers, accessed September 22, 2016, http://www.zevfacts.com/sales-dashboard.html.

187 "Low or No Emission Vehicle Program - 5339(c)," Federal Transit Administration, accessed October 21, 2016, https://www.transit.dot.gov/funding/grants/low-or-no-emission-vehicle-program-5339c.

188 "Voluntary Airport Low Emissions Program (VALE)," Federal Aviation Administration, accessed October 21, 2016, http://www.faa.gov/airports/environmental/vale/.

189 "Zero Emissions Airport Vehicle and Infrastructure Pilot Program," Federal Aviation Administration, accessed October 21, 2016, https://www.faa.gov/airports/environmental/zero_emissions_vehicles/.

[190] "Priorities for a Growing Geothermal Industry," Geothermal Energy Association, accessed July 25, 2016, http://geo-energy.org/priorities.aspx.

[191] William Opalka, "Q&A: NEPOOL Chair on Redesigning Market Rules for Low-Carbon Future," *RTO Insider* 2016, no. 32 (6 Sept. 2016): 9.

[192] Jim Lazar and Wilson Gonzalez, *Smart Rate Design for a Smart Future* (Montpelier, VT: Regulatory Assistance Project, 2015), 3.

[193] Carl Linvill, John Shenot, and Jim Lazar, *Designing Distributed Generation Tariffs Well: Fair Compensation in a Time of Transition* (Montpelier, VT: Regulatory Assistance Project, 2013).

[194] Ethan Howland, "Minnesota PUC Requires 'Value of Solar' for Utility's Community Gardens," *Public Power Daily*, July 26, 2016, http://www.publicpower.org/media/daily/ArticleDetail.cfm?ItemNumber=46180.

[195] "Fact Sheet: U.S. Reports its 2025 Emissions Target to the UNFCCC," The White House, Office of the Press Secretary, March 31, 2015, https://www.whitehouse.gov/the-press-office/2015/03/31/fact-sheet-us-reports-its-2025-emissions-target-unfccc.

[196] White House, *U.S. Cover Note INDC and Accompanying Information* (United Nations Framework Convention on Climate Change, March 2015), 2, http://www4.unfccc.int/Submissions/INDC/Published%20Documents/United%20States%20of%20America/1/U.S.%20Cover%20Note%20INDC%20and%20Accompanying%20Information.pdf.

[197] Intergovernmental Panel on Climate, *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by O. Edenhofer, R. Picks-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, T. Zwickel, and J. C. Minx (Cambridge, UK, and New York: Cambridge University Press, 2014), 10, http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf.

[198] The White House, Executive Office of the President, *The President's Climate Action Plan* (Washington, DC: The White House, June 2013), https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf.

[199] Environmental Protection Agency (EPA), *Regulatory Impact Analysis for the Clean Power Plan Final Rule* (Research Triangle Park, NC: EPA, 2015), EPA-452/R-15-003, https://www.epa.gov/sites/production/files/2015-08/documents/cpp-final-rule-ria.pdf.

[200] Trieu Mai, Wesley Cole, Eric Lantz, Cara Marcy, and Benjamin Sigrin, *Impacts of Federal Tax Credit Extensions on Renewable Deployment and Power Sector Emissions* (Golden, CO: 65571 National Renewable Energy Laboratory, 2016), NREL/TP-6A20-65571, http://www.nrel.gov/docs/fy16osti/65571.pdf.

[201] Trieu Mai, Wesley Cole, Eric Lantz, Cara Marcy, and Benjamin Sigrin, *Impacts of Federal Tax Credit Extensions on Renewable Deployment and Power Sector Emissions* (Golden, CO: 65571 National Renewable Energy Laboratory, 2016), NREL/TP-6A20-65571, http://www.nrel.gov/docs/fy16osti/65571.pdf.

[202] Environmental Protection Agency (EPA), "Air Pollutant Emissions Trends Data," EPA, last updated February 6, 2015, https://www.epa.gov/sites/production/files/2015-07/national_tier1_caps.xlsx.

[203] Department of Commerce, Bureau of Economic Analysis, "National Economic Accounts: Current-Dollar and 'Real' GDP," Department of Commerce, Bureau of Economic Analysis, accessed September 17, 2016, http://www.bea.gov/nationagdplevl/xls/.xls.

[204] Energy Information Administration (EIA), "Table 7.2a: Electricity Net Generation, Total (All Sectors)," *Monthly Energy Review*, August 2016: 113, http://www.eia.gov/totalenergy/data/monthly/#electricity.

[205] B. Brunekreef and B. Forsberg, "Epidemiological Evidence of Effects of Coarse Airborne Particles on Health," *European Respiratory Journal* 26, no. 2 (2005): 309–18, doi:10.1183/09031936.05.00001805.

[206] C. Arden Pope III and Douglas W. Dockery, "Health Effects of Fine Particulate Air Pollution: Lines that Connect," *Journal of the Air & Waste Management Association* 56, no. 6 (2006): 709–42, doi:10.1080/10473289.2006.10464485.

[207] "Progress Cleaning the Air and Improving People's Health," Environmental Protection Agency, last updated September 6, 2016, https://www.epa.gov/clean-air-act-overview/progress-cleaning-air-and-improving-peoples-health.

[208] Gabriel Chan, Robert Stavins, Robert Stowe, and Richard Sweeney, *The SO_2 Allowance Trading System and the Clean Air Act Amendments of 1990: Reflections on Twenty Years of Policy Innovation* (Cambridge, MA: Harvard Environmental Economics Program, January 2012), 5, https://www.hks.harvard.edu/m-rcbg/heep/papers/SO2-Brief_digital_final.pdf.

[209] National Acid Precipitation Assessment Program (NAPAP), *National Acid Precipitation Assessment Program Report to Congress: An Integrated Assessment* (Silver Spring, MD: NAPAP, 2005), http://www.esrl.noaa.gov/csd/AQRS/reports/napapreport05.pdf.

[210] Dallas Burtraw, *Cost Savings, Market Performance, and Economic Benefits of the U.S. Acid Rain Program* (Washington, DC: Resources for the Future, 1998), Discussion Paper 98-28-REV, http://www.rff.org/RFF/Documents/RFF-DP-98-28-REV.pdf.

[211] Ronald J. Shadbegian, Wayne B. Gray, and Cynthia L. Morgan, *Benefits and Costs from Sulfur Dioxide Trading: A Distributional Analysis* (Washington, DC: U.S. Environmental Protection Agency National Center for Environmental Economics, 2005), Working Paper 05-09, http://yosemite.epa.gov/ee/epa/eed.nsf/WPNumber/2005-09/$File/2005-09.PDF.

[212] Environmental Protection Agency (EPA), *The Benefits and Costs of the Clean Air Act from 1990 to 2020* (EPA, 2011), https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf.

[213] Environmental Protection Agency (EPA), "Table ES-3: Estimated Reduction in Incidence of Adverse Health Effects of the Mercury and Air Toxics Standards (95% confidence intervals)," in *Regulatory Impact Analysis for the Final Mercury and Air Toxics Standards* (Research Triangle Park, NC: EPA, 2011), EPA-452/R-11-011, ES-5, https://www.epa.gov/sites/production/files/2015-11/documents/matsriafinal.pdf.

[214] Environmental Protection Agency (EPA), *The Benefits and Costs of the Clean Air Act from 1990 to 2020* (EPA, 2011), https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf.

[215] Maureen Hinman and Amy Kreps, *2016 Top Markets Report: Environmental Technologies* (Department of Commerce, International Trade Administration, 2016), 3, http://trade.gov/topmarkets/pdf/Environmental_Technologies_Top_Markets_Report.pdf.

[216] Network of Heads of the European Environment Protection Agencies (EPA Network), *The Contribution of Good Environmental Regulation to Competitiveness* (EPA Network, November 2005), 3, http://epanet.pbe.eea.europa.eu/fol249409/our-publications/2691_prague-new.pdf/download/en/1/2691_prague-new.pdf.

[217] Maureen Hinman and Amy Kreps, *2016 Top Markets Report: Environmental Technologies* (Department of Commerce, International Trade Administration, 2016), 3, http://trade.gov/topmarkets/pdf/Environmental_Technologies_Top_Markets_Report.pdf.

[218] Massachusetts Institute of Technology, *The Future of Natural Gas* (Cambridge, MA: Massachusetts Institute of Technology, 2011), 29, 163.

[219] Massachusetts Institute of Technology, *The Future of Natural Gas* (Cambridge, MA: Massachusetts Institute of Technology, 2011), 29, 163.

[220] Department of Energy, *Revolution Now: The Future Arrives for Five Clean Energy Technologies – 2016 Update* (Washington, DC: DOE, 2016), 8, https://energy.gov/sites/prod/files/2016/09/f33/Revolutiona%CC%82%E2%82%ACNow%202016%20Report_2.pdf.

[221] Department of Energy, *Solid-State Lighting Patents Resulting from DOE-Funded Projects* (Department of Energy, Building Technologies Office, 20160, 1, https://energy.gov/sites/prod/files/2016/01/f28/patents_factsheet_jan2016.pdf.

[222] Department of Energy, *Solid-State Lighting Commercial Product Development Resulting from DOE-Funded Projects* (Department of Energy, Building Technologies Office, 2016), 1–4, https://energy.gov/sites/prod/files/2015/07/f24/comm-product-factsheet_jun2015.pdf.

[223] Department of Energy, *Revolution Now: The Future Arrives for Five Clean Energy Technologies – 2016 Update* (Washington, DC: DOE, 2016), 8, https://energy.gov/sites/prod/files/2016/09/f33/Revolutiona%CC%82%E2%82%ACNow%202016%20Report_2.pdf.

[224] Paula Mints, *Photovoltaic Manufacturer Capacity, Shipments, Price & Revenues 2015/2016* (SPV Market Research, April 2016), Report SPV-Supply3.

[225] Paula Mints, *Photovoltaic Manufacturer Capacity, Shipments, Price & Revenues 2014/2015* (SPV Market Research, April 2015), Report SPV-Supply3.

[226] Navigant Consulting, *Photovoltaic Manufacturer Shipments, Capacity & Competitive Analysis 2009/2010* (Navigant Consulting, April 2010), Report NPS-Supply5.

[227] Navigant Consulting, *Photovoltaic Manufacturer Shipments 2005/2006* (Navigant Consulting, August 2006), Report NPS-Supply1.

[228] Strategies Unlimited, *Photovoltaic Manufacture Shipments and Profiles, 2001–2003* (Strategies Unlimited, September 2003), Report SUMPM 53.

[229] The White House, Executive Office of the President of the United States, *The Economic Record of the Obama Administration: Addressing Climate Change* (Washington, DC: The White House, September 2016), 11, https://www.whitehouse.gov/sites/default/files/page/files/20160921_record_climate_energy_cea.pdf.

[230] "Welcome," Regional Greenhouse Gas Initiative, accessed October 6, 2016, https://www.rggi.org/.

[231] "Fact Sheet: The Investment of RGGI Proceeds through 2014," Regional Greenhouse Gas Initiative, https://www.rggi.org/docs/ProceedsReport/RGGI_Proceeds_FactSheet_2014.pdf.

[232] "Assembly Bill 32 Overview," California Environmental Protection Agency Air Resources Board, accessed December 15, 2016, https://www.arb.ca.gov/cc/ab32/ab32.htm.

[233] "What's New List Serve Post Display," California Environmental Protection Agency Air Resources Board, May 26, 2016 https://www.arb.ca.gov/lispub/rss/displaypost.php?pno=9472.

[234] Thaddeus Huetteman, "California and Quebec complete second joint carbon dioxide emissions allowance auction," Energy Information Administration, *Today in Energy*, March 11, 2015, https://www.eia.gov/todayinenergy/detail.php?id=20312.

[235] LuAnn Dahlman, "Climate Change: Global Temperatures," National Oceanic and Atmospheric Administration (January 1, 2015), https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature.

[236] LuAnn Dahlman, "Climate Change: Global Temperatures," National Oceanic and Atmospheric Administration, January 1, 2015, https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature.

[237] Patrick Lynch, "2016 Climate Trends Continue to Break Records," National Aeronautics and Space Administration, last updated July 19, 2016, http://www.nasa.gov/feature/goddard/2016/climate-trends-continue-to-break-records.

[238] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2013: The Physical Science Basis Contribution from Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Summary for Policymakers*, edited by Thomas F. Stocker, Dahe Qin, Gian-kasper Plattner, Melinda M. B. Tignor, Simon K. Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M. Midgley (IPCC, 2013), https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf.

[239] Allen Fawcett, Gokul C. Iyer, Leon E. Clarke, James A. Edmonds, Nathan E. Hultman, Haweon C. McJeon, Joeri Rogelj, et al., "Can Paris Pledges Avert Severe Climate Change? Reducing Risks of Severe Outcomes and Improving Chances of Limiting Warming to 2°C," *Science* 350, no. 62650 (2015), doi:10.1126/science.aad5761.

[240] "CAIT Climate Data Exporter," World Resources Institute, accessed October 20, 2016, http://cait.wri.org/indc/#/.

[241] United Nations Framework Convention on Climate Change (UNFCCC), *Paris Agreement*, (UNFCCC, 2015), http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

[242] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: Synthesis Report Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland: IPCC, 2007), https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

[243] Intergovernmental Panel on Climate Change, *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (Cambridge, UK, and New York: Cambridge University Press, 2014), http://ipcc-wg2.gov/AR5/report.

[244] The White House, Office of the Press Secretary, "U.S. Leadership and the Historic Paris Agreement to Combat Climate Change," The White House, December 12, 2015, https://www.whitehouse.gov/the-press-office/2015/12/12/us-leadership-and-historic-paris-agreement-combat-climate-change.

[245] The White House, U.*S. Cover Note INDC and Accompanying Information* (United Nations Framework Convention on Climate Change, March 2015), http://www4.unfccc.int/Submissions/INDC/Published%20Documents/United%20States%20of%20America/1/U.S.%20Cover%20Note%20INDC%20and%20Accompanying%20Information.pdf.

[246] The White House, Office of the Press Secretary, "FACT SHEET: U.S.-China Cooperation on Climate Change," The White House, September 3, 2016, https://www.whitehouse.gov/the-press-office/2016/09/03/fact-sheet-us-china-cooperation-climate-change-0.

[247] Department of State, *2016 Second Biennial Report of the United States of America* (Department of State, 2016), http://unfccc.int/files/national_reports/biennial_reports_and_iar/submitted_biennial_reports/application/pdf/2016_second_biennial_report_of_the_united_states_.pdf.

[248] The White House, Executive Office of the President of the United States, *The Economic Record of the Obama Administration: Addressing Climate Change* (Washington, DC: The White House, 2016), 11, https://www.whitehouse.gov/sites/default/files/page/files/20160921_record_climate_energy_cea.pdf.

[249] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[250] Department of Energy, *Carbon Capture, Utilization, and Storage: Climate Change, Economic Competitiveness, and Energy Security* (Washington, DC: Department of Energy, 2016), http://energy.gov/sites/prod/files/2016/09/f33/DOE%20-%20Carbon%20Capture%20Utilization%20and%20Storage_2016-09-07.pdf.

[251] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[252] Department of Energy, *Carbon Capture, Utilization, and Storage: Climate Change, Economic Competitiveness, and Energy Security* (Washington, DC: Department of Energy, 2016), 8, http://energy.gov/sites/prod/files/2016/09/f33/DOE%20-%20Carbon%20Capture%20Utilization%20and%20Storage_2016-09-07.pdf.

[253] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[254] Department of Energy, *Carbon Capture, Utilization, and Storage: Climate Change, Economic Competitiveness, and Energy Security* (Washington, DC: Department of Energy, 2016), https://energy.gov/fe/downloads/doe-white-paper-carbon-capture-utilization-and-storage .

[255] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[256] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[257] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[258] Department of Energy (DOE), *Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and* Policy (Washington, DC: DOE, 2017).

[259] Executive Office of the President, President's Council of Advisors on Science and Technology, *The Energy Imperative: Technology and the Role of Emerging Companies* (Washington, DC: President's Council of Advisors on Science and Technology, 2006), viii.

[260] Executive Office of the President, President's Council of Advisors on Science and Technology, *The Energy Imperative: Technology and the Role of Emerging Companies* (Washington, DC: President's Council of Advisors on Science and Technology, 2006), 40.

[261] American Energy Innovation Council (AEIC), *A Business Plan for America's Energy Future* (Washington, DC: AEIC, 2010), 3.

[262] Executive Office of the President, President's Council of Advisors on Science and Technology, *Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy* (Washington, DC: President's Council of Advisors on Science and Technology, 2010), vii, 1–2, 13–15.

[263] Letha Tawney, Francisco Almendra, Pablo Torres, and Lutz Weischer, "Two Degress of Innovation—How to Seize the Opportunities in Low-Carbon Power," (Washington, DC: World Resources Institute, 2011), Working Paper, 3.

[264] International Institute for Applied Systems Analysis, *Global Energy Assessment* (Cambridge, MA: Cambridge University Press, 2012), 1670–1.

[265] American Energy Innovation Council, *Restoring American Energy Innovation Leadership: Report Card, Challenges and Opportunities* (Washington, DC: Bipartisan Policy Center, 2015), 13–7, http://americanenergyinnovation.org/wp-content/uploads/2015/02/AEIC-Restoring-American-Energy-Innovation-Leadership-2015.pdf.

[266] Richard K. Lester and David M. Hart, *Unlocking Energy Innovation: How America Can Build a Low-Cost, Low-Carbon Energy System* (Cambridge, MA: MIT Press Books, 2012), 51.

[267] Frankfurt School FS-UNEP Collaborating Centre, *Global Trends in Renewable Energy Investment 2016* (Frankfurt School of Finance & Management, 2016), 14. http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2016lowres_0.pdf.

[268] Benjamin Gaddy, Varun Sivaram, and Francis O'Sullivan, *Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation* (MIT Energy Initiative, July 2016), Working Paper, 2–3, 6, 11.

[269] American Energy Innovation Council (AEIC), *A Business Plan for America's Energy Future* (Washington, DC: AEIC, 2010), 6.

[270] National Research Council, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000* (National Academies Press, 2001), 35, 197, doi:10.17226/10165.

[271] American Energy Innovation Council (AEIC), *A Business Plan for America's Energy Future* (Washington, DC: AEIC, 2010), 4, 12.

[272] American Energy Innovation Council, *Catalyzing American Ingenuity: The Role of Government in Energy Innovation* (Washington, DC: American Energy Innovation Council, 2011), 5.

[273] Charles Weiss and William B. Bonvillian, *Structuring an Energy Technology Revolution* (Cambridge, MA: MIT Press, 2012), 31.

[274] President's Committee of Advisors on Science and Technology (PCAST), *Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-First Century* (Washington, DC: PCAST, 1997), https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nov2007.pdf.

[275] John P. Holdren, William K. Reilly, John W. Rowe, Philip Sharp, and Jason Grumet, *Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges* (The National Commission on Energy Policy, 2004), 103–5, http://belfercenter.hks.harvard.edu/publication/4000/ending_the_energy_stalemate.html?breadcrumb=%2Fpublication%2Fby_type%2Facademic_papers_reports%3Fgroupby%3D0%26%3D%26filter%3D2004.

[276] The National Commission on Energy Policy, *Energy Policy Recommendations to the President and 110th Congress* (The National Commission on Energy Policy, 2007), 22–3, http://bipartisanpolicy.org/wp-content/uploads/sites/default/files/Energy%20Policy%20Recommendations%20to%20the%20President%20and%20the%20110th%20Congress.pdf.

[277] Executive Office of the President, President's Council of Advisors on Science and Technology, *The Energy Imperative: Technology and the Role of Emerging Companies* (Washington, DC: President's Council of Advisors on Science and Technology, 2006), ix.

[278] International Energy Agency, *Global Gaps in Clean Energy Research, Development, and Demonstration* (Paris, France: International Energy Agency, 2009), 51–2.

[279] American Energy Innovation Council (AEIC), *A Business Plan for America's Energy Future* (Washington, DC: AEIC, 2010), 4, 20.

[280] Executive Office of the President, President's Council of Advisors on Science and Technology, *Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy* (Washington, DC: President's Council of Advisors on Science and Technology, 2010), 13–5.

[281] American Energy Innovation Council (AEIC), *Catalyzing American Ingenuity: The Role of Government in Energy Innovation* (AEIC, 2011), 813.

[282] American Energy Innovation Council, *Restoring American Energy Innovation Leadership: Report Card, Challenges and Opportunities,* (Washington, DC: Bipartisan Policy Center, 2015), 6–7, 13–17, http://americanenergyinnovation.org/wp-content/uploads/2015/02/AEIC-Restoring-American-Energy-Innovation-Leadership-2015.pdf.

[283] Charles Weiss and William B. Bonvillian, *Structuring an Energy Technology Revolution* (Cambridge, MA: MIT Press, 2012), 149.

[284] National Academy of Sciences, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington DC: National Academies Press, 2016), 5, 10–1, doi:10.17226/21712.

[285] America Competes Act, 42 U.S.C § 149, Subchapter XVII, as amended by Sec. 5012 of P.L. 110-69 (H.R. 2272) and Sec. 904 of P.L. 111-358 (H.R. 5116).

[286] E. Williams and D. Henshall, *Advanced Research Projects Agency-Energy Mission Innovation Context: Overview of Commercialization Activities* (ARPA-E, August 31, 2016).

[287] T. Heidel, "GENI Program Overview & Introductions" (presented at GENI Annual Program Review, New Orleans, LA, January 14–15, 2015), http://arpa-e.energy.gov/sites/default/files/A_GENI%20Intro_Heidel.pdf.

[288] Electric Power Research Institute (EPRI), *Benefits and Value of New Power Flow Controllers,* July 2016 Draft (EPRI, forthcoming).

[289] Executive Office of the President, President's Council of Advisors on Science and Technology, *Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy* (President's Council of Advisors on Science and Technology, 2010), 4.

[290] Varun Sivaram and Teryn Norris, "The Clean Energy Revolution: Fighting Climate Change With Innovation," *Foreign Affairs* 95 (May/June 2016), 2, https://www.foreignaffairs.com/articles/united-states/2016-04-18/clean-energy-revolution.

[291] National Academy of Sciences, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (National Academies Press, 2016), 5–6, doi:10.17226/21712.

[292] Executive Office of the President, President's Council of Advisors on Science and Technology, *University-Private Sector Research Partnerships in the Innovation Ecosystem* (President's Council of Advisors on Science and Technology, 2008), 4.

[293] International Energy Agency, *Global Gaps in Clean Energy Research, Development, and Demonstration* (Paris, France: International Energy Agency, 2009), 53.

[294] International Institute for Applied Systems Analysis, *Global Energy Assessment* (Camrbidge, MA: Cambridge University Press, 2012), 1710–1.

[295] Thomas Perry, Mackay Miller, Lee Fleming, Kenneth Younge, and James Newcomb, *Clean Energy Innovation: Sources of Technical and Commercial Breakthroughs* (Golden, CO: National Renewable Energy Laboratory, 2011), Technical Report, 30.

[296] Gretchen Jordan, Jonathan Mote, Rosalie Ruegg, Thomas Choi, and Angela Becker-Dippmann, *A Framework for Evaluating R&D Impacts and Supply Chain Dynamics Early in a Product Life Cycle—Looking Inside the Black Box of Innovation,* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2014), Technical Report, 1.

[297] "'Enabling Framework' for Mission Innovation," Inaugural Ministerial of Mission Innovation, accessed December 15, 2016, http://mission-innovation.net/wp-content/uploads/2016/06/MI-Enabling-Framework-1-June-2016.pdf.

[298] The White House, *Domestic Implementation Framework for Mission Innovation*: *Accelerating the Pace of American Clean Energy Research, Development, and Demonstration through Proven and Powerful Approaches* (Washington, DC: The White House, November 2016), https://www.whitehouse.gov/sites/default/files/omb/reports/final_domestic_mission_innovation_framework_111616_700pm.pdf

[299] Patrick Kiker, "New Report Finds Energy Efficiency is America's Cheapest Energy Resource," American Council for an Energy-Efficient Economy, March 25, 2014, http://aceee.org/press/2014/03/new-report-finds-energy-efficiency-a.

[300] Advanced Energy Economy, *Advanced Energy Now 2016 Market Report* (Advanced Energy Economy, March 2016), http://info.aee.net/aen-2016-market-report.

[301] International Renewable Energy Agency, *Renewable Energy and Jobs, Annual Review 2016* (Abu Dhabi: International Renewable Energy Agency, 2016), http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Jobs_Annual_Review_2016.pdf.

[302] Sharmen Hettipola, "Fact Sheet: Jobs in Renewable Energy and Energy Efficiency (2015)," Environmental and Energy Study Institute, November 6, 2015, http://www.eesi.org/papers/view/fact-sheet-jobs-in-renewable-energy-and-energy-efficiency-2015.

[303] The White House, *Domestic Implementation Framework for Mission Innovation*: *Accelerating the Pace of American Clean Energy Research, Development, and Demonstration through Proven and Powerful Approaches* (Washington, DC: The White House, November 2016), 2, https://www.whitehouse.gov/sites/default/files/omb/reports/final_domestic_mission_innovation_framework_111616_700pm.pdf.

[304] International Finance Corporation (IFC), *Climate Investment Opportunities in Emerging Markets, An IFC Analysis* (Washington, DC: IFC, 2016), http://www.ifc.org/wps/wcm/connect/2b169cd5-e5c2-411a-bb71-be1eaff23301/3503-IFC-Climate_Investment_Opportunity-Report-FINAL-11_7_16.pdf?MOD=AJPERES.

[305] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), "Chapter VII: Addressing Environmental Aspects of TS&D Infrastructure," in *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), 7–3, http://www.energy.gov/epsa/quadrennial-energy-review-first-installment.

306 "Coal-Fired Characteristics and Controls: 2015, Table of Coal Unit Characteristics," Environmental Protection Agency, accessed June 2, 2016, https://www.epa.gov/airmarkets/emissions-tracking-highlights.

307 Dallas Burtraw, et al. 1998. "Costs and Benefits of Reducing Air Pollutants Related to Acid Rain," *Contemporary Economic Policy* 16, no. 4 (1998): 379–400.

308 Environmental Protection Agency, *Benefits and Costs of the Clean Air Act 1990-2020, the Second Prospective Study* (Washington, DC: Environmental Protection Agency, Office of Air and Radiation, 2011), https://www.epa.gov/clean-air-act-overview/analytical-components-benefits-and-costs-clean-air-act-1990-2020-second.

309 National Research Council, Committee on Health, Environmental, Other External Costs, Benefits of Energy Production, and Consumption, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (National Academies Press, 2010).

310 Nicholas Z. Muller and Robert Mendelsohn, "Efficient Pollution Regulation: Getting the Prices Right," *The American Economic Review* (2009): 1714–1739, 1734, http://www.jstor.org/stable/25592534.

311 Nicholas Z. Muller, Robert Mendelsohn, and William Nordhaus, "Environmental Accounting for Pollution in the United States Economy," *The American Economic Review* (2011): 1649–1675, http://www.jstor.org/stable/23045618.

312 74 Fed. Reg. 239, 66496–66546 (December 15, 2009).

313 "Climate and Health Assessment," U.S. Global Research Program, accessed December 28, 2016, https://health2016.globalchange.gov/.

314 "Climate Change and Human Health," U.S. Global Research Program, accessed December 28, 2016, https://health2016.globalchange.gov/climate-change-and-human-health.

315 J. Balbus, A. Crimmins, J. L. Gamble, D. R. Easterling, K. E. Kunkel, S. Saha, and M. C. Sarofim, "Climate Change and Human Health," in *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (Washington, DC: U.S. Global Change Research Program, 2016), 25–42, http://dx.doi.org/10.7930/J0VX0DFW.

316 J. Balbus, A. Crimmins, J. L. Gamble, D. R. Easterling, K. E. Kunkel, S. Saha, and M. C. Sarofim, "Climate Change and Human Health," in *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (Washington, DC: U.S. Global Change Research Program, 2016), 25–42, http://dx.doi.org/10.7930/J0VX0DFW.

317 Nicholas Z. Muller, Robert Mendelsohn, and William Nordhaus, "Environmental Accounting for Pollution in the United States Economy," *The American Economic Review* (2011): 1649–1675, http://www.jstor.org/stable/23045618.

318 N. Z. Muller and R. O. Mendelsohn, "Measuring the Damages of Air Pollution in the United States," *Journal of Environmental Economics and Management* 54, no. 1 (2007): 1–14.

319 Industrial Economics, *Health and Welfare Benefits Analyses to Support the Second Section 812 Benefit-Cost Analysis of the Clean Air Act* (Cambridge, MA: Industrial Economics, 2011).

320 Environmental Protection Agency (EPA), *Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter* (Research Triangle Park, NC: EPA Office of Air Quality Planning and Standards, Health and Environmental Impacts Division, 2012), EPA-452/R-12-005, Table 5-2, https://www3.epa.gov/ttn/ecas/regdata/RIAs/finalria.pdf.

321 "Air Pollutant Emissions Trends Data, 1970–2014," Environmental Protection Agency, accessed April 7, 2016, https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

322 "Mercury and Air Toxics Standards," Environmental Protection Agency, accessed December 21, 2016, https://www3.epa.gov/mats/powerplants.html.

323 Emanuele Massetti, Marilyn Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li, *Environmental Quality and the U.S. Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice* (Oak Ridge, TN: Oak Ridge National Laboratory, 2016). ORNL/SPR-2016/772, 156.

324 "Emissions Tracking Highlights Table of Coal Unit Characteristics: 2015," Environmental Protection Agency, accessed May 17, 2016, https://www.epa.gov/sites/production/files/2016-05/coalunitcharacteristics2015.xls.

325 "Steam Electric Power Generating Effluent Guidelines," Environmental Protection Agency, accessed April 11, 2016, https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines.

326 "Steam Electric Power Generating Effluent Guidelines," Environmental Protection Agency, accessed April 11, 2016, https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines.

[327] "Environmental Assessment for the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category, September 2015," Environmental Protection Agency, accessed April 20, 2016, https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines-2015-final-rule-documents.

[328] Environmental Protection Agency (EPA), *Environmental Assessment for the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category* (Washington, DC: EPA, 2015), EPA-821-R-15-006, https://www.epa.gov/sites/production/files/2015-10/documents/steam-electric-envir_10-20-15.pdf.

[329] Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category: Final Rule, 40 C.F.R. § 423.

[330] Intergovernmental Panel on Climate Change, *Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, MA: Cambridge University Press, 2001).

[331] Department of Energy (DOE), *The Water-Energy Nexus: Challenges and Opportunities* (DOE, 2014), DOE/EPSA-0002.

[332] Deborah Elcock, *Reducing Freshwater Consumption at Coal-Fired Power Plants: Approaches Used Outside the United States* (National Energy Technology Laboratory, 2011), DOE/NETL-2011/1493.

[333] U.S. Geological Survey (USGS), "Summary of Estimated Water Use in the United States in 2010," USGS, November 2014, Fact Sheet 2014-3109, https://pubs.usgs.gov/fs/2014/3109/pdf/fs2014-3109.pdf.

[334] "Estimated Use of Water in the United States County-Level Data for 2010," U.S. Geological Survey, accessed September 13, 2016, http://water.usgs.gov/watuse/data/2010/index.html.

[335] Energy Information Administration (EIA), "Electricity, Form EIA-860 Detailed Data," (Washington, DC: EIA, 2016), DOE/EIA-860(2015); Energy Information Administration (EIA), https://www.eia.gov/electricity/data/eia860/.

[336] Energy Information Administration (EIA), "Electricity, Form EIA-923 Detailed Data," EIA, November, 30, 2016, https://www.eia.gov/electricity/data/eia923/.

[337] Department of Energy (DOE), *The Water-Energy Nexus: Challenges and Opportunities* (DOE, 2014), DOE/EPSA-0002.

[338] K. Averyt, J. Macknick, J. Rogers, N. Madden, J. Fisher, J. Meldrum, and R. Newmark, "Water Use for Electricity in the United States: An Analysis of Reported and Calculated Water Use Information for 2008," *Environmental Research Letters* 8, no. 1 (2013): 015001, doi:10.1088/1748-9326/8/1/015001.

[339] Energy Information Administration (EIA), *Net Generation by State by Type of Producer by Energy Source Data* (Washington, DC: EIA, 2016), DOE/EIA-923(2015).

[340] Energy Information Administration (EIA), *Net Generation by State by Type of Producer by Energy Source Data* (Washington, DC: EIA, 2016), DOE/EIA-923(2015).

[341] Molly A. Maupin, Joan F. Kenny, Susan S. Hutson, John K Lovelace, Nancy L. Barber, Kristin S. Linsey, *Estimated Use of Water in the United States in 2010* (Reston, VA: U.S. Geological Survey, 2014), Circular 1405.

[342] Energy Information Administration (EIA), *Annual Energy Review 2011* (Washington, DC: EIA, 2012), DOE/EIA-0384(2011).

[343] Molly A. Maupin, Joan F. Kenny, Susan S. Hutson, John K Lovelace, Nancy L. Barber, Kristin S. Linsey, *Estimated Use of Water in the United States in 2010* (Reston, VA: U.S. Geological Survey, 2014), Circular 1405.

[344] Energy Information Administration (EIA), *Annual Energy Review 2011* (Washington, DC: EIA, 2012), DOE/EIA-0384(2011).

[345] "Thermoelectric Cooling Water Data," Energy Information Administration, 2016, https://www.eia.gov/electricity/data/water/.

[346] Deborah Elcock, *Reducing Freshwater Consumption at Coal-Fired Power Plants: Approaches Used Outside the United States* (National Energy Technology Laboratory, 2011), DOE/NETL-2011/1493.

[347] Haibo Zhai and Edward S. Rubin, "Performance and Cost of Wet and Dry Cooling Systems for Pulverized Coal Power Plants with and without Carbon Capture And Storage," *Energy Policy* 38, no. 10 (October 2010): 5653–60, doi:10.1016/j.enpol.2010.05.013.

[348] Energy Information Administration (EIA), *Net Generation by State by Type of Producer by Energy Source Data* (Washington, DC: EIA, 2016), DOE/EIA-923(2015).

[349] Energy Information Administration (EIA), "Electricity, Form EIA-860 Detailed Data" (Washington, DC: EIA, 2016), DOE/EIA-860(2015).

[350] "Thermoelectric Cooling Water Data," Energy Information Administration, https://www.eia.gov/electricity/data/water/.

[351] Department of Energy (DOE), *The Water-Energy Nexus: Challenges and Opportunities* (DOE, 2014), DOE/EPSA-0002.

[352] National Energy Technology Laboratory (NETL), *Cost and Performance Baseline for Fossil Energy Plants Vol 1a: Bituminous Coal (PC) and Natural gas to Electricity* (Pittsburgh, PA: NETL, 2015), https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Rev3Vol1aPC_NGCC_final.pdf.

[353] Advanced Research Projects Agency-Energy (ARPA-E), "ARID Program Overview," (Washington, DC: ARPA-E, 2016), https://arpa-e.energy.gov/sites/default/files/documents/files/ARID_ProgramOverview.pdf.

[354] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), "Chapter VII: Addressing Environmental Aspects of TS&D Infrastructure," in *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), 7-3, http://www.energy.gov/epsa/quadrennial-energy-review-first-installment.

[355] EURELECTRIC*, Life Cycle Assessment of Electricity Generation* (WG Environmental Management & Economics, 2011), 14, http://www.eurelectric.org/media/26740/report-lca-resap-final-2011-420-0001-01-e.pdf.

[356] Vasilis Fthenakis and Hyung Chul Kim, "Land Use and Electricity Generation: A Life-Cycle Analysis," *Renewable and Sustainable Energy Reviews* 13, no. 6-7 (2009): 1465–1474.

[357] National Renewable Energy Laboratory (NREL), *Renewable Electricity Futures Study*, edited by M. M. Hand, S. Baldwin, E. DeMeo, J. M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, and D. Sandor (Golden, CO: NREL, 2012), NREL/TP-6A20-52409, A-66, Table A-10, http://www.nrel.gov/analysis/re_futures/.

[358] Vasilis Fthenakis and Hyung Chul Kim, "Land Use and Electricity Generation: A Life-Cycle Analysis," *Renewable and Sustainable Energy Reviews* 13, no. 6-7 (2009): 1465–1474, Figure 2, http://www.sciencedirect.com/science/article/pii/S1364032108001354.

[359] Timothy Skone, James Littlefield, Joe Marriott, Greg Cooney, Matt Jamieson, Jeremie Hakian, and Greg Schivley*, Life Cycle Analysis of Natural Gas Extraction and Power Generation* (National Energy Technology Laboratory, 2014), DOE/NETL-2014/1646, http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Life%20Cycle%20Analysis/NETL-NG-Power-LCA-29May2014.pdf.

[360] Vasilis Fthenakis and Hyung Chul Kim, "Land Use and Electricity Generation: A Life-Cycle Analysis," *Renewable and Sustainable Energy Reviews* 13, no. 6-7 (2009): 1465–1474, Figure 2, http://www.sciencedirect.com/science/article/pii/S1364032108001354.

[361] Jeffrey Logan, Garvin Heath, Jordan Macknick, Elizabeth Paranhos, William Boyd, and Ken Carlson, *Natural Gas and the Transformation of the U.S. Energy Sector: Electricity* (Golden, CO: National Renewable Energy Laboratory, 2012), NREL/TP-6A50-55538, 85, http://www.nrel.gov/docs/fy13osti/55538.pdf.

[362] U.S. Department of Energy, Induced Seismicity, July 2016, http://energy.gov/sites/prod/files/2016/08/f33/Induced%20Seismicity.pdf, accessed December 15, 2016

[363] U.S. Environmental Protection Agency, The Effects of Mountaintop Mines and Valley Fills on Aquatic Ecosystems of the Central Appalachian Coalfields (2011 Final), https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=225743&CFID=63330774&CFTOKEN=63962894, accessed December 16, 2016

[364] Department of Energy (DOE), *Wind Vision: A New Era for Wind Power in the United States* (DOE, 2015), DOE/GO-102015-4557, http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf.

[365] Massachusetts Institute of Technology (MIT), *The Future of Solar Energy* (MIT, 2015).

[366] Massachusetts Institute of Technology (MIT), *The Future of Solar Energy* (MIT, 2015), 129.

[367] National Renewable Energy Laboratory (NREL), *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*, (NREL, 2016), NREL/TP-6A20-65298, 34.

[368] Benjamin K. Sovacool, "Valuing the Greenhouse Gas Emissions from Nuclear Power: A Critical Survey," *Energy Policy* 36 (2008): 2940–53.

369 Benjamin K. Sovacool, "The Avian and Wildlife Costs of Fossil Fuels and Nuclear Power," *Journal of Integrative Environmental Sciences* 9, no. 4 (2012): 255–278, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2198024; Benjamin K. Sovacool, "Contextualizing Avian Mortality: A Preliminary Appraisal of Bird and Bat Fatalities from Wind, Fossil-Fuel, and Nuclear Electricity," *Energy Policy* 37, no. 6 (2009): 2241–2248, http://dx.doi.org/10.1016/j.enpol.2009.02.011.

370 Benjamin K. Sovacool, "Valuing the Greenhouse Gas Emissions from Nuclear Power: A Critical Survey," *Energy Policy* 36 (2008): 2940–53.

371 Leroy J. Walston, Jr., et al., *A Review of Avian Monitoring and Mitigation Information at Existing Utility-Scale Solar Facilities* (Argonne National Laboratory, April 2015), ANL/EVS-15/2, http://www.evs.anl.gov/downloads/ANL-EVS_15-2.pdf.

372 "ISEGS Avian and Bat Monitoring Plan, 2014-2015 Annual Report," Western EcoSystems Technology, Inc., June 2016. http://www.eenews.net/assets/2016/07/29/document_gw_01.pdf

373 Leroy J. Walston, Jr., et al., *A Review of Avian Monitoring and Mitigation Information at Existing Utility-Scale Solar Facilities* (Argonne National Laboratory, April 2015), ANL/EVS-15/2, http://www.evs.anl.gov/downloads/ANL-EVS_15-2.pdf.

374 Department of Energy (DOE) and Department of the Interior (DOI), *Programmatic Environmental Impact Statement on Solar Energy Development on BLM-Administered Lands in the Southwestern United States* (DOE and DOI, 2012), http://solareis.anl.gov/.

375 "Environmental Impacts and Siting of Wind Projects," Department of Energy, Office of Energy Efficiency and Renewable Energy, https://energy.gov/eere/wind/environmental-impacts-and-siting-wind-projects; "Energy Department Announces New Projects to Help Protect Wildlife at Wind Energy Plants," Department of Energy, Office of Energy Efficiency and Renewable Energy, April 14, 2015, https://energy.gov/eere/articles/energy-department-announces-new-projects-help-protect-wildlife-wind-energy-plants.

376 Department of Energy (DOE), *Wind Vision: A New Era for Wind Power in the United States* (DOE, 2015), DOE/GO-102015-4557, Table 2-8, http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf.

377 Dale Strickland, et al., *Comprehensive Guide to Studying Wind Energy/Wildlife Interactions* (Washington, DC: Department of Energy, Wind and Water Power Program, June 2011), https://www.batcon.org/pdfs/wind/National%20Wind%20Coordinating%20Collaborative%202011_Comprehensive%20Guide%20to%20Studying%20Wind%20Energy%20and%20Wildlife%20Interactions.pdf.

378 "Hydropower Generators Produce Clean Electricity, but Hydropower Does Have Environmental Impacts," Energy Information Administration, accessed April 5, 2016, http://www.eia.gov/Energyexplained/?page=hydropower_environment.

379 "Hydropower Market Acceleration and Deployment," Department of Energy, accessed December 16, 2016, https://energy.gov/eere/water/hydropower-market-acceleration-and-deployment#impacts.

380 Stephen K. Ritter, "A New Life for Coal Ash," *Chemical & Engineering News* 94, no. 7 (2016): 10–14.

381 Richard Martin and Mackinnon Lawrence, *Coal Plant Decommissioning* (Navigant Research, 2013).

382 American Coal Ash Association, *2014 Coal Combustion Product Production & Use Survey Report*, https://www.acaa-usa.org/Portals/9/Files/PDFs/2014ReportFinal.pdf.

383 Electric Power Research Institute (EPRI), *Coal Ash: Characteristics, Management, and Environmental Issues* (Palo Alto, CA: EPRI, 2009), doi:1019022.

384 Mara Hvistendahl, "Coal Ash is More Radioactive Than Nuclear Waste," *Scientific American*, December 13, 2007, http://www.scientificamerican.com/article/coal-ash-is-more-radioactive-than-nuclear-waste/.

385 B. Hoen et al., *A Spatial Hedonic Analysis of the Effects of Wind Energy Facilities on Surrounding Property Values in the United States* (Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, August 2013), https://emp.lbl.gov/sites/all/files/lbnl-6362e.pdf.

386 "Changes to the Ecosystem," Foundation for Water & Energy Education, accessed April 5, 2016, http://fwee.org/environment/how-a-hydroelectric-project-can-affect-a-river/changes-to-the-ecosystem/.

387 "Geothermal Power Plants – Minimizing Land Use and Impact," Department of Energy, Geothermal Technologies Office, accessed December 15, 2016, http://energy.gov/eere/geothermal/geothermal-power-plants-minimizing-land-use-and-impact

388 Ernie Major, James Nelson, Ann Robertson-Tait, Jean Savy, and Ivan Wong, *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Department of Energy, Geothermal Technologies Program, 2012), DOE/EE-0662, https://www1.eere.energy.gov/geothermal/pdfs/geothermal_seismicity_protocol_012012.pdf

[389] Anders Arvesen, Ingrid Bjerke Hauan, Bernhard Mikal Bolsoy, Edgar G. Hertwich, "Life Cycle Assessment of Transport of Electricity via Different Voltage Levels: A Case Study for Nord-Trondelag County in Norway," *Applied Energy* 157 (2015): 144–51, doi:10.1016/j.apenergy.2015.08.013.

[390] Grace C. Wu, Margaret S. Torn, and James H. Williams, "Incorporating Land-Use Requirements and Environmental Constraints in Low-Carbon Electricity Planning for California," *Environmental Science & Technology* 49, no. 4 (2015): 2013–21, doi:10.1021/es502979v.

[391] Rodolfo Araneo, Luigi Martirano, and Salvatore Celozzi, "Low-Environmental Impact Routeing of Overhead Power Lines for the Connection of Renewable Energy Plants to the Italian HV Grid," in *Conference Proceedings: 2014 14th International Conference On Environment And Electrical Engineering (EEEIC)* (2014), 386–91.

[392] Public Service Commission of Wisconsin, *Environmental Impacts of Transmission Lines* (Public Service Commission of Wisconsin, 2013), 6, http://psc.wi.gov/thelibrary/publications/electric/electric10.pdf.

[393] Electric Power Research Institute (EPRI), "T&D and ROW Environmental Issues – Program 51, Program Overview," in *2014 Research Portfolio* (EPRI, 2014), http://mydocs.epri.com/docs/Portfolio/P2014/2014_P051.pdf.

[394] Sebastien Rioux, Jean-Pierre L. Savard, and Alyssa A. Gerick, "Avian Mortalities Due to transmission Line Collisions: A Review of Current Estimates and Field Methods with an Emphasis on Applications to the Canadian Electric Network," *Avian Conservation and Ecology* 8, no. 2 (2013): 7, doi:10.5751/ACE-00614-080207.

[395] Albert Manville, "Bird Strikes and Electrocutions at Power Lines, Communication Towers, and Wind Turbines: State of the Art and State of the Science – Next Steps Toward Mitigation." USDA Forest Service 1052. 2005. http://www.fs.fed.us/psw/publications/documents/psw_gtr191/Asilomar/pdfs/1051-1064.pdf. Accessed May 16, 2016 Page 1055.

[396] "Summary of Clean Air Act," Environmental Protection Agency, https://www.epa.gov/laws-regulations/summary-clean-air-act.

[397] "Summary of the Clean Water Act," Environmental Protection Agency, https://www.epa.gov/laws-regulations/summary-clean-water-act.

[398] "Endangered Species Act Overview," Fish and Wildlife Service, https://www.fws.gov/endangered/laws-policies/.

[399] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), 9-4, http://www.energy.gov/epsa/quadrennial-energy-review-first-installment.

[400] 42 U.S.C. § 4321–4347 (1970); 40 C.F.R. § 1500–1508 (1978).

[401] Dan Utech, "Modernizing our Electric Transmission Infrastructure and Driving the Development of Clean Energy," The White House Blog, July 21, 2015, https://www.whitehouse.gov/blog/2015/07/21/modernizing-our-electric-transmission-infrastructure-and-driving-development-clean-e.

[402] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), 7-6, http://www.energy.gov/epsa/quadrennial-energy-review-first-installment.

[403] 40 C.F.R. § 1508.20 (1978).

[404] "Section 404 of the Clean Water Act: Policy and Guidance," Environmental Protection Agency, accessed March 9, 2015, http://water.epa.gov/lawsregs/guidance/wetlands/ wetlandsmitigation_index.cfm.

[405] Compensatory Mitigation for Losses of Aquatic Resources, 73 Fed. Reg. 19594 (April 10, 2008) (40 C.F.R. § 230), https://www.gpo.gov/fdsys/pkg/FR-2008-04-10/pdf/E8-6918.pdf.

[406] Department of the Interior Bureau of Land Management, "Instruction Memorandum No. 2013-142 – Interim Policy, Draft - Regional Mitigation Manual Section – 1794," June 13, 2013, http://www.blm.gov/wo/st/en/info/regulations/Instruction_Memos__and_Bulletins/national_instruction/2013/IM_2013-142.html; Department of the Interior (DOI), Energy and Climate Change Task Force, *A Strategy for Improving the Mitigation Policies and Practices of the Department of the Interior* (DOI, April 2014), www.doi.gov/news/upload/Mitigation-Report-to-the-Secretary_FINAL_04_08_14.pdf; "The BLM's Landscape Approach for Managing Public Lands," Department of the Interior, Bureau of Land Management, last updated February 11, 2016, http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach.html; NiSource, Inc., Record of Decision, Habitat

Conservation Plan, Environmental Impact Statement, and Permit Issuance, 78 Fed. Reg. 68465 (November 14, 2013), http://www.gpo.gov/fdsys/pkg/FR-2013-11-14/pdf/2013-27230.pdf.

[407] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), "Chapter IX: Siting and Permitting of TS&D Infrastructure," in *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), http://energy.gov/sites/prod/files/2015/08/f25/QER%20Chapter%20IX%20Siting%20and%20Permitting%20April%202015.pdf

[408] Government Accountability Office (GAO), *National Environmental Policy Act: Little Information Exists on NEPA Analyses*, Report to Congressional Requesters (GAO, 2014), GAO-14-370, http://www.gao.gov/assets/670/662546.pdf.

[409] James A. Holtkamp and Mark A. Davidson, *Transmission Siting in the Western United States: Overview and Recommendations Prepared as Information to the Western Interstate Energy Board* (Holland & Hart, 2009), https://www.hollandhart.com/articles/transmission_siting_white_paper_final.pdf.

[410] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), "Chapter IX: Siting and Permitting of TS&D Infrastructure," in *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), http://energy.gov/sites/prod/files/2015/08/f25/QER%20Chapter%20IX%20Siting%20and%20Permitting%20April%202015.pdf

[411] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), "Chapter IX: Siting and Permitting of TS&D Infrastructure," in *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), 9-4, http://energy.gov/sites/prod/files/2015/08/f25/QER%20Chapter%20IX%20Siting%20and%20Permitting%20April%202015.pdf

[412] Dan Utech, "Modernizing our Electric Transmission Infrastructure and Driving the Development of Clean Energy," The White House Blog, July 21, 2015, https://www.whitehouse.gov/blog/2015/07/21/modernizing-our-electric-transmission-infrastructure-and-driving-development-clean-e.

[413] Dan Utech, "Modernizing our Electric Transmission Infrastructure and Driving the Development of Clean Energy," The White House Blog, July 21, 2015, https://www.whitehouse.gov/blog/2015/07/21/modernizing-our-electric-transmission-infrastructure-and-driving-development-clean-e.

[414] "Plains & Eastern EIS," Department of Energy, accessed December 19, 2016, http://www.plainsandeasterneis.com/.

[415] "Great Northern Transmission Line EIS," Department of Energy, accessed December 19, 2016, http://www.greatnortherneis.org/.

[416] "New England Clean Power Line Project," Department of Energy, accessed December 19, 2016, http://necplinkeis.com/.

[417] "Tethys Platform," Brigham Young University, accessed December 13, 2016, http://www.tethysplatform.org/.

[418] "Tethys," Pacific Northwest National Laboratory, accessed June 2, 2016, http://tethys.pnnl.gov/about-tethys.

[419] "Wind-Wildlife Impacts Literature Database (WILD)," National Renewable Energy Laboratory, accessed June 2, 2016. https://wild.nrel.gov/.

[420] Benjamin K. Sovacool, *The Dirty Energy Dilemma: What's Blocking Clean Power in the United States* (Praeger, 2008).

[421] Environmental Protection Agency (EPA), *RE-Powering America's Land: Siting Renewable Energy on Potentially Contaminated land, Landfills and Mine Sites* (EPA, 2015), http://www.epa.gov/sites/production/files/2015-03/documents/repower_technologies_solar.pdf.

[422] Department of Energy (DOE), *Wind Vision: A New Era for Wind Power in the United States* (DOE, 2015), DOE/GO-102015-4557, http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf.

[423] Candace McKinley and Derek Sandison*, What Is the Difference Between a Programmatic and a Project-Level Environmental Impact Statement?* (Department of Ecology, State of Washington, November 2013), http://www.usbr.gov/pn/programs/eis/kkc/scoping/progsite.pdf.

[424] "Preliminary Monthly Electric Generator Inventory," Energy Information Administration, November 29, 2016, http://www.eia.gov/electricity/data/eia860m/.

[424] Stephen K. Ritter, "A New Life for Coal Ash," *Chemical & Engineering News* 94, no. 7 (2016): 10–14.

[424] Richard Martin and Mackinnon Lawrence, *Coal Plant Decommissioning* (Navigant Research, 2013).

[425] U.S. Environmental Protection Agency, Regulatory Impact Analysis for the Final Mercury and Air Toxics Standards, (December 2011), https://www3.epa.gov/ttn/ecas/regdata/RIAs/matsriafinal.pdf

[426] J. Balbus, A. Crimmins, J. L. Gamble, D. R. Easterling, K. E. Kunkel, S. Saha, and M. C. Sarofim, "Climate Change and Human Health," in *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (Washington, DC: U.S. Global Change Research Program, 2016), 249, http://dx.doi.org/10.7930/J0VX0DFW

[427] Pepco Energy Services, "Benning Road Power Plant: Decommissioning and Demolition Project," (presented at the MD-DC Utilities Association Conference, Cambridge, MD, October 22, 2014), 6, http://static1.squarespace.com/static/527154c0e4b09a993f80e460/t/545d17f6e4b042c56b56e272/1415387126360/McNulty_PPR_Demo_MD-DCUtilities_Presentation_Final.pdf.

[428] J. Balbus, A. Crimmins, J. L. Gamble, D. R. Easterling, K. E. Kunkel, S. Saha, and M. C. Sarofim, "Climate Change and Human Health," in *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (Washington, DC: U.S. Global Change Research Program, 2016), 256–257, http://dx.doi.org/10.7930/J0VX0DFW.

[429] Hong Kong Environment Protection Department, "Chapter 5.3: Water Quality" and "Chapter 5.4: Waste Management," in *Decommissioning of Two Open Cycle Gas Turbine Units and Associated Facilities at Tsing Yi Power Station*" (Island East, Hong Kong: Environmental Resource Management, 2003), http://www.epd.gov.hk/eia/register/profile/latest/dir090.pdf.

[430] U.S. Geological Survey (USGS), *Naturally Occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment—An Issue for the Energy Industry* (Denver, CO: USGS, 1999), FS-142-99, 3, http://pubs.usgs.gov/fs/fs-0142-99/fs-0142-99.pdf.

[431] Environmental Protection Agency (EPA), *Regulatory Impact Analysis for EPA's 2015 RCRA Final Rule Regulating Coal Combustion Residue (CCR) Landfills and Surface Impoundments at Coal-Fired Electric Utility Power Plants* (EPA, 2015), EPA-HQ-OW-2009-081906375, DCN SE06111, 8-8–8-11.

[432] U.S. Geological Survey (USGS), *Naturally Occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment—An Issue for the Energy Industry* (Denver, CO: USGS, 1999), FS-142-99, 3, http://pubs.usgs.gov/fs/fs-0142-99/fs-0142-99.pdf.

[433] Environmental Protection Agency (EPA), *Environmental Justice (EJ) Interagency Workging Group (IWG) Promising Practices for EJ Methodologies in NEPA Reviews* (EPA, March 2016), EPA Pub. No: 300-B-16-001, https://www.epa.gov/sites/production/files/2016-08/documents/nepa_promising_practices_document_2016.pdf, accessed December 13, 2016

[434] Department of Energy (DOE), Office of Energy Policy and Systems Analysis (EPSA), *Quadrennial Energy Review First Installment: Energy Transmission, Storage, and Distribution Infrastructure* (Washington, DC: DOE-EPSA, 2015), 7-3–7-6, http://www.energy.gov/epsa/quadrennial-energy-review-first-installment.

[435] "Preliminary Monthly Electric Generator Inventory," Energy Information Administration, February 26, 2016, accessed March 13, 2016, http://www.eia.gov/electricity/data/eia860m.

[436] Energy Information Administration, *Electric Power Monthly*, https://www.eia.gov/electricity/monthly/.

[437] Richard Martin and Mackinnon Lawrence, *Coal Plant Decommissioning* (Navigant Research, 2013).

[438] Stephen K. Ritter, "A New Life for Coal Ash," *Chemical & Engineering News* 94, no. 7 (2016): 10–4.

[439] Nancy Slater-Thompson, "Nuclear Regulatory Commission Resumes License Renewals for Nuclear Power Plants," Energy Information Administration, *Today in Energy,* October 29, 2014, http://www.eia.gov/todayinenergy/detail.cfm?id=18591

[440] "Questions and Answers Decommissioning Planning Final Rule," Nuclear Regulatory Commission, April 10, 2015.

[441] Nuclear Regulatory Commission (NRC), "Decommissioning Nuclear Power Plants," *Backgrounder: Office of Public Affairs* Fact Sheet (NRC, May 1, 2015), http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html.

[442] "Disposal of High Level Nuclear Waste," Government Accountability Office, accessed June 9, 2015. http://www.gao.gov/key_issues/disposal_of_highlevel_nuclear_waste/issue_summary.

[443]Pepco Energy Services, "Benning Road Power Plant: Decommissioning and Demolition Project," (presented at the MD-DC Utilities Association Conference, Cambridge, MD, October 22, 2014), 6, http://static1.squarespace.com/static/527154c0e4b09a993f80e460/t/545d17f6e4b042c56b56e272/1415387126360/McNulty_PPR_Demo_MD-DCUtilities_Presentation_Final.pdf.

[444] Hong Kong Environment Protection Department, “Chapter 5.3: Water Quality” and “Chapter 5.4: Waste Management,” in *Decommissioning of Two Open Cycle Gas Turbine Units and Associated Facilities at Tsing Yi Power Station*” (Island East, Hong Kong: Environmental Resource Management, 2003), http://www.epd.gov.hk/eia/register/profile/latest/dir090.pdf.

[445] U.S. Geological Survey (USGS), *Naturally Occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment—An Issue for the Energy Industry* (Denver, CO: USGS, 1999), FS-142-99, http://pubs.usgs.gov/fs/fs-0142-99/fs-0142-99.pdf.

[446] U.S. Geological Survey (USGS), *Naturally Occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment—An Issue for the Energy Industry* (Denver, CO: USGS, 1999), FS-142-99, 3, http://pubs.usgs.gov/fs/fs-0142-99/fs-0142-99.pdf.

[447] Canadian Solar Aria, *Decommissioning Plan Report* (Guelph, ON: Aria Solar, 2012), http://ariasolarproject.com/Aria%20-%20Nov%202013/Aria%20Tab%204%20-%20Decommissioning%20Plan%20Report.pdf.

[448] Apple One, *Apple One Solar Farm Decommissioning Plan* (Charlotte, NC: Birdseye Manager LLC, December 12, 2014), http://www.catawbacountync.gov/Planning/Projects/Rezonings/RZ2014-06Decommission.pdf.

[449] U.S. Department of the Interior, Bureau of Land Management, Instruction Memorandum No. 2015-138, Change1, (Washington DC, December 2015, https://www.blm.gov/wo/st/en/info/regulations/Instruction_Memos_and_Bulletins/national_instruction/2015/im_2015-138__change.html