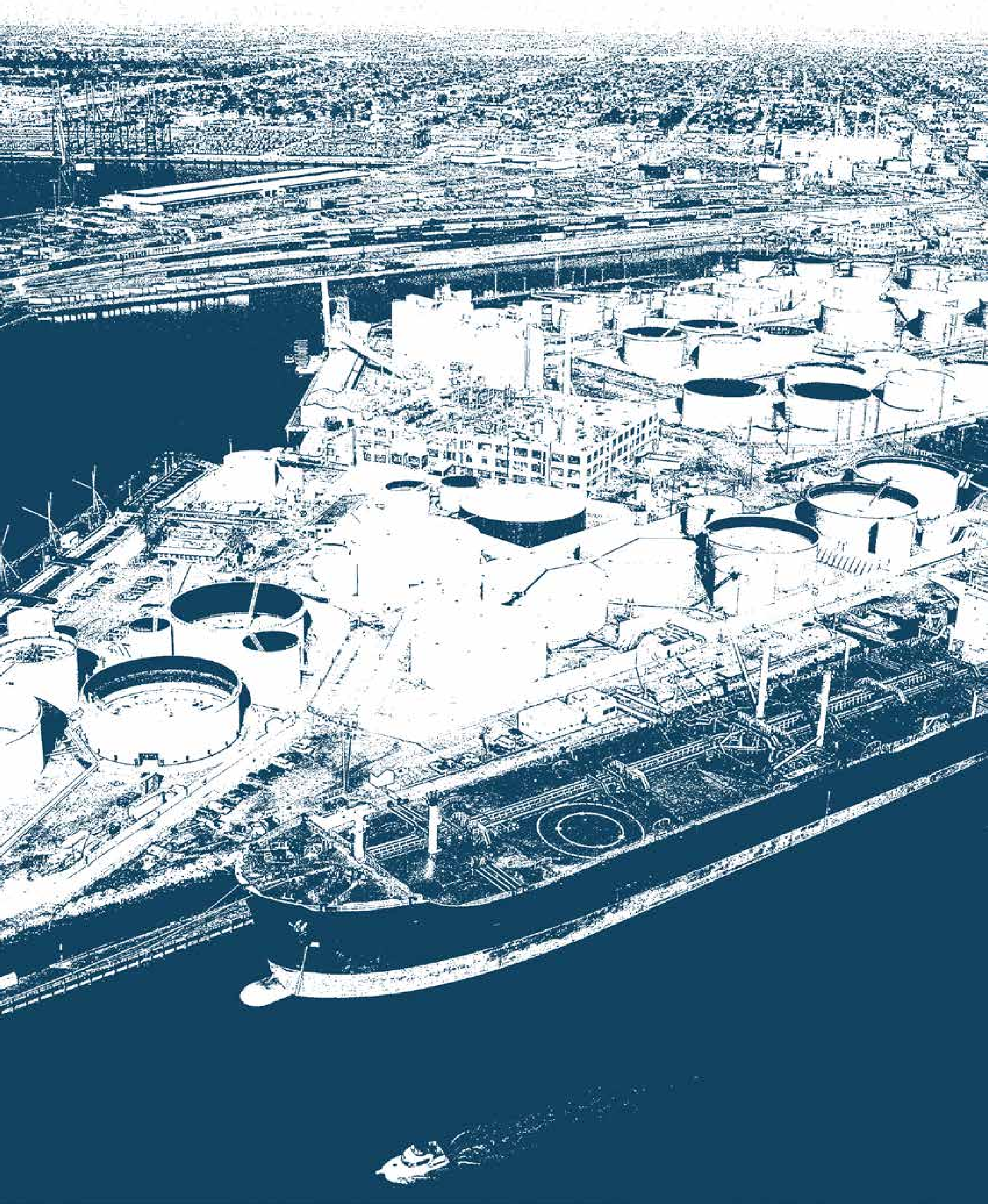


Chapter I

INTRODUCTION

This chapter provides a general introduction to transmission, storage, and distribution (TS&D) infrastructure issues and to the report. It describes why TS&D infrastructure is important to the U.S. energy system. It then covers a set of trends and issues affecting the current U.S. TS&D infrastructure and the demands it will need to meet going forward. Finally, the chapter briefly describes the objectives that informed the study's development and the architecture of the report that resulted.

The Character of the Nation's TS&D Infrastructure

The United States has one of the most advanced energy systems in the world, supplying the reliable, affordable, and increasingly clean power and fuels that underpin every facet of the Nation's economy and way of life. The energy TS&D infrastructure—defined here as *the infrastructure that links energy supplies, energy carriers, or energy by-products to intermediate and end users*—is large, complex, and interdependent. It includes approximately 2.6 million miles of interstate and intrastate pipelines; 414 natural gas storage facilities; 330 ports handling crude petroleum and refined petroleum products; and more than 140,000 miles of railways that handle crude petroleum, refined petroleum products, liquefied natural gas (LNG), and coal. The electrical component of the Nation's TS&D infrastructure links more than 19,000 individual generators with a capacity of 1 megawatt or more (sited at more than 7,000 operational power plants), with more than 642,000 miles of high-voltage transmission lines and 6.3 million miles of distribution lines.[1, 2]

The critical importance of these infrastructure facilities is not only in linking energy system components with each other and with end users across the Nation; they also link the U.S. energy system to the rest of the world. The TS&D infrastructure elements considered in this report are listed in Table 1-1.

Table 1-1. Elements of TS&D Infrastructure Considered in this Installment of the QER[3]

Fuel/Energy Carrier	TS&D Infrastructure Element/System
Electricity	Transmission lines and substations
	Distribution lines and distributed generation
	Electricity storage
	Other electric grid-related infrastructure
Natural Gas	Natural gas gathering lines
	Transmission pipelines
	Natural gas storage facilities
	Processing facilities
	Distribution pipelines and systems
	LNG production/storage facilities (including export terminals)
Coal	Rail, truck, barge transport
	Export terminals
Crude Oil/ Petroleum Products	Crude oil pipelines
	Crude oil and products import and export terminals
	Rail, truck, barge transport
	Oil refineries
	Strategic Petroleum Reserve & Regional Petroleum Product Reserves
	CO_2 pipelines (including for enhanced oil recovery)
Biofuels	Transport of feedstock and derived products, biorefineries

The requirements that this TS&D infrastructure must meet are extensive and demanding. It must handle a diverse and evolving mix of energy sources and energy products; link sources, processors, and users across immense distances; match demands that vary on multiple time scales; co-exist with competing uses of the same systems (e.g., ports and railways); and perform 24 hours a day, 365 days a year with high reliability, which in turn requires both low susceptibility to disruptions and the resilience to recover quickly from whatever disruptions nonetheless occur. The longevity and high capital costs of energy TS&D infrastructure, moreover, mean that decisions made about how to locate, expand, and otherwise modify this infrastructure today will be influencing—either enabling or constraining—the size and composition of the national energy system for decades to come.

Much of the TS&D infrastructure is owned and operated by the private sector, and a significant portion of the legal, regulatory, and policy development and implementation around such infrastructure occurs at state and local levels. At the same time, the Federal Government controls and operates substantial TS&D infrastructure assets of its own, including inland waterways, thousands of miles of transmission lines, and strategic oil and product reserves. Some of the infrastructure elements owned by others are federally regulated with respect to aspects of siting, safety, environment, and reliability. Additionally, a number of emergency authorities bearing on TS&D infrastructure are vested in the Federal Government.

A further complexity affecting the TS&D infrastructure management and policy is that these infrastructures often reach across state and even international boundaries, thus affecting large regions and making multi-state and sometimes multi-national coordination essential for modernization, reliability, resilience, and flexibility. In addition, the large capital costs, scale, and "natural monopoly" characteristics of much TS&D infrastructure tend to perpetuate the role of incumbent providers; these circumstances constrain innovation and add to the usual litany of market failures—public goods, externalities, information deficits, perverse incentives—generally understood to warrant intervention through government policy when the proposed remedy is expected to have sufficient net benefits to overcome predicable ancillary and unintended consequences.

Given the complexity of this policy landscape, it should be obvious that Federal policies to encourage and enable modernization and expansion of the Nation's TS&D infrastructure must be well coordinated with state, local, tribal, and (sometimes) international jurisdictions and with full consideration of the interaction of policy at all levels of government with private sector incentives and capabilities, to include attention to opportunities for well-designed, purpose-driven, public-private partnerships.

Trends Affecting TS&D Infrastructure Choices

The U.S. energy landscape is in a time of transition. The relevant trends include dramatic changes in the pattern of domestic coal, petroleum, and natural gas production; a drastically altered outlook for energy imports and exports; large increases in electricity generation from wind and sunlight; and an increased priority on moving rapidly to reduce greenhouse gas (GHG) emissions from the energy sector. All of these trends have significant implications for the Nation's TS&D infrastructure. So does another trend that has been building for decades, which is a lack of timely investment in refurbishing, replacing, and modernizing components of that infrastructure that are simply old or obsolete. These trends and their implications for TS&D infrastructure are elaborated briefly in the subsections that follow.

Aging Infrastructure and Changing Requirements

More than a decade ago, a Department of Energy (DOE) report pronounced the U.S. electricity grid "aging, inefficient, congested, and incapable of meeting the future energy needs of the information economy without significant operational changes and substantial public-private capital investment over the next several decades."[4] Although significant improvements have been made to the grid since then, the basic conclusion of the need to modernize the grid remains valid. The Edison Electric Institute estimated in 2008 that by 2030 the U.S. electric utility industry will need to make a total infrastructure investment of between $1.5 trillion and $2.0 trillion, of which transmission and distribution investment is expected to account for about $900.0 billion.[5]

Modernization of the grid has been made all the more urgent by the increasing and now virtually pervasive dependence of modern life on a reliable supply of electricity. Without that, navigation, telecommunication, the financial system, healthcare, emergency response, and the Internet, as well as all that depends on it, become unreliable. Yet, the threats to the grid—ranging from geomagnetic storms that can knock out crucial transformers; to terrorist attacks on transmission lines and substations; to more flooding, faster sea-level rise, and increasingly powerful storms from global climate change—have been growing even as society's dependence on the grid has increased.

In addition, changes in the expectations and desires of businesses and individual consumers have been altering what the grid is expected to do. Once satisfied with a simple arrangement where utilities provided services and consumers bought power on fixed plans, now individuals and companies want to control the production and delivery of their electricity, and technology has become available to implement those wishes. These trends, coupled with flat or declining electricity demand, could dramatically alter current utility business models, and they are already making it more important to appropriately value and use distributed generation, smart grid technologies, and storage.

Natural gas and oil TS&D infrastructures likewise pose aging and obsolescence concerns. These infrastructures simply have not kept pace with changes in the volumes and geography of oil and gas production. The Nation's ports, waterways, and rail systems are congested, with the growing demands for handling energy commodities increasing in competition with transport needs for food and other non-energy freight, and much of the relevant infrastructure—pipelines, rail systems, ports, and waterways alike—is long overdue for repairs, not to mention modernization.

One compelling example is the infrastructure for moving natural gas. Close to 50 percent of the Nation's gas transmission and gathering pipelines were constructed in the 1950s and 1960s—a build-out of the interstate pipeline network to respond to the thriving post-World War II economy (see Figure 1-1). Analyses conducted for the Quadrennial Energy Review (QER) suggest that natural gas interstate pipeline investment will range between $2.6 billion and $3.5 billion per year between 2015 and 2030, depending on the overall level of natural gas demand. The total cost of replacing cast iron and bare steel pipes in gas distribution systems is estimated to be $270 billion.[a]

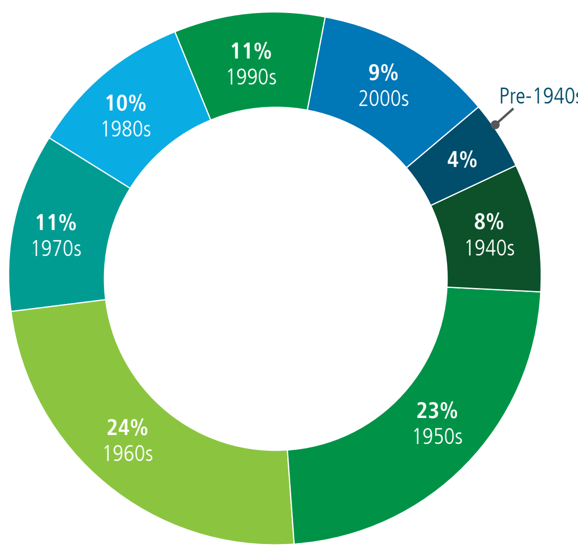


Figure 1-1. Age by Decade of U.S. Gas Transmission and Gathering Pipelines[6]

Nearly 60 percent of U.S. natural gas transmission and gathering lines are at least 45 years old, and 35 percent are 55 years old or older.

[a] The American Gas Association reports that the total cost of replacing all cast iron pipe in the United States would be about $83 billion in 2011 dollars. American Gas Association. "Managing the Reduction of the Nation's Cast Iron Inventory." 2013. www.aga.org/managing-reduction-nation%E2%80%99s-cast-iron-inventory. Accessed January 16, 2015. According to Pipeline and Hazardous Materials Safety Administration data, cast iron pipes represent approximately 30 percent of the total leak-prone pipe in the United States. Therefore, assuming other pipe replacement has similar costs, the total cost for replacement of all leak-prone pipe is roughly $270 billion.

Increases in U.S. Oil and Natural Gas Production and Proved Reserves

The United States is the world's largest combined producer of petroleum and natural gas. In just 2 years, U.S. oil production increased by 35 percent from 2011 to 2013.[7] U.S. proved reserves[b] of crude oil and lease condensates increased each year from 2009 through 2013 and now total more than 36 billion barrels—a level not seen for almost four decades.[8] Some of this increased production has been in locations that did not have sufficient pipeline capacity to accommodate it. For example, proved reserves of crude oil and lease condensate in North Dakota recently surpassed those of the Federal waters in the Gulf of Mexico, ranking North Dakota second only to Texas among U.S. oil-producing states.[9]

Industry has responded to the infrastructure gap by expanding pipeline capacity where it can; reversing flow direction on other pipelines; converting natural gas lines to oil; and seeking new "workaround" solutions to transportation bottlenecks by moving increasing amounts of oil by truck, barge, and rail.

The profile for U.S. natural gas production and reserves is similar. Between 2005 and 2013, U.S. production increased by 28 percent, and in 2013, proved natural gas reserves in the United States hit 354 trillion cubic feet—a new record.[10] In 2013, shale gas was 38 percent of U.S. production and 47 percent of proved gas reserves;[11, 12] between 2010 and 2013, shale gas production increased by 114 percent.[13] The geography of gas production and reserves has also changed dramatically. Seventy percent of net increases in proved gas reserves are in just two states: Pennsylvania and West Virginia.[14] This production is also occurring in locations where natural gas has not been produced in the past, changing movement of product flows and placing demands on the infrastructure to move this product to consumers.

Decreases in Oil Consumption

At the same time that U.S. oil production has been growing markedly, U.S. oil consumption, and particularly consumption of a major refined product (gasoline), has been falling.[15] A number of factors have led to the decrease in oil consumption. The Administration has set historic fuel economy standards for light and heavy vehicles in recent years, which are already having an impact. In October 2014, a record was set for new light-duty vehicle efficiency in the United States, reaching 24.1 miles per gallon.[16] By 2025, passenger and light-duty trucks are expected to be more than twice as efficient, reaching an average of 54.5 miles per gallon.[17] Many of these vehicles are hybrid or electric; widespread deployment of hybrid vehicles could substantially reduce oil demand, and wide-scale deployment of electric vehicles would require changes to the United States' current infrastructure. An increase in natural gas heavy-duty vehicles is projected; this is unlikely to make a significant difference in TS&D infrastructure requirements.[18]

The Energy Information Administration (EIA) forecasts show a slight drop in oil demand by 2040 as a result of these standards; this is a significant change from previous forecasts, which anticipated increases in fuel demand in 2040.[19] The Renewable Fuel Standard also requires that a mandated volume of renewable fuels (such as ethanol and biodiesel) to be blended into U.S. transportation fuels. In 2012, ethanol consumption reached nearly 10 percent of U.S. gasoline demand by volume.[20] After decades of growth, U.S. vehicle miles traveled dropped between 2007 and 2008 and have been relatively flat since.[21] Specifically, from 1971 through 1995, average vehicle miles traveled growth was approximately 3 percent per year; this growth rate dropped to about 2 percent per year from 1996 through 2007 and has been close to 0 percent from 2008 to 2012. Vehicle miles traveled *per capita* actually peaked a few years earlier in 2004 and has continued to decline.[22] Finally, a proportion of the decline in fuel consumption is the result of reduced demand during the contraction of the economy in 2008 to 2009.

[b] Proved reserves are estimated volumes of hydrocarbon resources that analysis of geologic and engineering data demonstrates with reasonable certainty are recoverable under existing economic and operating conditions. Reserve estimates change from year to year as new discoveries are made, existing fields are more thoroughly appraised, existing reserves are produced, and prices and technologies change. See: Energy Information Administration. "U.S. Crude Oil and Natural Gas Proved Reserves." December 19, 2014. www.eia.gov/naturalgas/crudeoilreserves/.

Reductions in Net Oil Imports

As a consequence of both increased oil production and decreased oil consumption, net petroleum imports to the United States have declined steadily and significantly in recent years. The United States is currently less dependent on foreign oil than it has been in over 40 years. In 2005, net U.S. imports of crude oil and petroleum products averaged about 12.5 million barrels per day (million bbl/d) of a total of 20.8 million bbl/d of product supplied; by year-end 2014, net imports of crude oil and petroleum products exceeded 5.0 million bbl/d of a total of 19.6 million bbl/d.[23, 24, 25] This decrease in net petroleum imports has improved the energy and economic security of the United States. The United States remains, however, a large crude oil importer and petroleum product exporter;[26] these links into the global market also link the United States to global oil prices and oil price volatility. Continued attention to infrastructure (e.g., the Strategic Petroleum Reserve) that addresses those vulnerabilities is needed.

Increases in Petroleum Product and Natural Gas Exports

U.S. exports of crude oil and petroleum products have increased dramatically. In 2005, the United States exported 1.2 million bbl/d of crude oil and petroleum products (gasoline, distillate, jet fuel, petroleum coke, and hydrocarbon gas liquids); by October 2014, this amount grew to around 4.0 million bbl/d of crude oil and petroleum products.[27] Almost 92 percent of total exports are refined products from oil; only 8 percent of the total is crude oil.[28] Many of these refined products are produced or shipped from the Gulf of Mexico, which has increased the flow of petroleum and petroleum products in TS&D infrastructure flowing in that direction.

In addition, the United States is positioned to become a major exporter of natural gas just 10 years after an accelerated development of significant import capacity. Rising supplies and falling natural gas costs in the United States opened a price gap with other parts of the world and eliminated most of the need to import LNG. In response, developers have started to repurpose previously constructed LNG import terminals to allow exports. Approved LNG export permits to Free Trade Agreement and non-Free Trade Agreement countries are about 40 billion cubic feet per day (Bcf/d) and 5.74 Bcf/d, respectively. Total capacity of natural gas pipelines to Mexico was 6.5 Bcf/d in 2008,[29, 30] and by 2016, EIA projects that the United States will be exporting more than 1 trillion cubic feet of natural gas to Mexico annually.[31] This additional capacity is meant to serve anticipated growing demand from Mexico's electric power sector.[32]

Onshoring of Energy-Intensive Industries

According to the Congressional Budget Office, without shale gas, U.S. natural gas prices would be 70 percent higher than projected prices by 2040.[33] The availability of lower-cost natural gas and natural gas liquids (NGL) provides an advantage for U.S. manufacturers using natural gas or NGL for heat, power, or feedstocks. As NGL costs have decreased, process costs for U.S. petrochemical manufacturing, which commonly uses NGL as a feedstock, have also decreased. This has enabled some U.S. petrochemical facilities to gain an export advantage over other parts of the world.[34] As a result, many expansions and additions to the U.S. petrochemical manufacturing sector have been announced. The industrial sector as a whole has also taken advantage of abundant natural gas. U.S. industrial consumption of natural gas has increased 15 percent from 2007 to 2014.[35] The 2014 Annual Energy Outlook Reference case projects industrial consumption of natural gas and petroleum to increase substantially from 2014 levels by 2025 and NGL and petrochemical feedstock consumption to increase 44 percent from 2014 levels by 2025.[36] Many of these increased operations will require access to, and be sited near, natural gas and NGL TS&D infrastructure. As a result, in 2014, renewable energy (including hydropower) made up almost 13 percent of U.S. electricity generation.[37]

Increased Deployment of Renewable Energy for Power Generation

Renewable energy deployment in the United States is rising. From 2008 to the end of 2013, the amount of electricity generated from wind energy has more than tripled, and the amount from solar has increased by more than tenfold.[38] Renewable energy systems, including hydropower, wind, biomass, geothermal, and solar, generated 523 million megawatt-hours of electricity in the United States in 2013.[39] According to EIA, in the first 6 months of 2014, 26 percent of the 4,396 megawatts of new utility-scale installed generating capacity that came online were solar additions and one-sixth were wind. Solar additions were up 67 percent over the same time period in 2013 and wind more than doubled.[40]

One important driver of increased renewable energy generation for electricity has been falling costs. Photovoltaic solar modules cost about 1 percent of what they did 35 years ago.[41] Analysis by the National Renewable Energy Laboratory has found that the average cost for a utility-scale photovoltaic project in the United States dropped from about $0.21 per kilowatt-hour in 2010 to $0.11 per kilowatt-hour at the end of 2013.[42] A second driver for increased renewable electricity generation has been state-level Renewable Portfolio Standards. Thirty-eight states have Renewable Portfolio Standards or some kind of preference or goal for renewables.[43] Almost all states have met their targets for 2013.[44] A third important driver has been the Production Tax Credit.

The increase in renewable electricity has changed demands on TS&D infrastructure. Some significant renewable resources are located far from population centers, and construction of adequate TS&D infrastructure is key to accessing those resources. Another element of TS&D infrastructure—energy storage—may also become more important as a means of integrating higher amounts of intermittent renewables into the electric grid. At present, though, the many options for managing and operating the grid have lessened demand for long-distance transmission, though this could strand some high-value resources in both the midcontinent and offshore, particularly where there is no nearby demand. Power companies have multiple options for meeting state Renewable Portfolio Standards, and depending on how they choose to comply, there will be more or less need for additional transmission and distribution systems, particularly interstate TS&D infrastructure. For example, Texas requires the use of indigenous renewable resources for power generation to meet its standard. While it is the only state to do so explicitly, 17 other states offer a range of preferences for in-state renewable generation sources, including rebates or upfront cash incentives, income or franchise tax incentives, property or sales tax incentives, Property Assessed Clean Energy or low-interest financing, grant programs, feed-in tariffs, and bond funding.[45] With respect to energy storage, while it is an important enabler for variable renewables, the lack of available energy storage is not yet a limiting factor for expansion of renewable electricity generation.

Increased Use of Natural Gas for Power Generation

Abundant natural gas supply and comparatively low prices have also affected the economics of electric power markets. Additionally, recent environmental regulations at the local, state, regional, and Federal levels have encouraged switching to fuels with lower emissions profiles, including natural gas and renewables. Natural gas demand for power generation grew from 15.0 Bcf/d in 2005 to 21.4 Bcf/d in 2013, and it is projected to increase by another 6.2 Bcf/d by 2030.[46, 47, c] Electricity generation from natural gas rose by 85 percent nationally from 2000 to 2013—from 601 terawatt-hours in 2000 to 1,114 terawatt-hours in 2013.[48] To better understand the scale of natural gas use, total U.S. natural gas consumption in 2013 was 71.6 Bcf/d.[49]

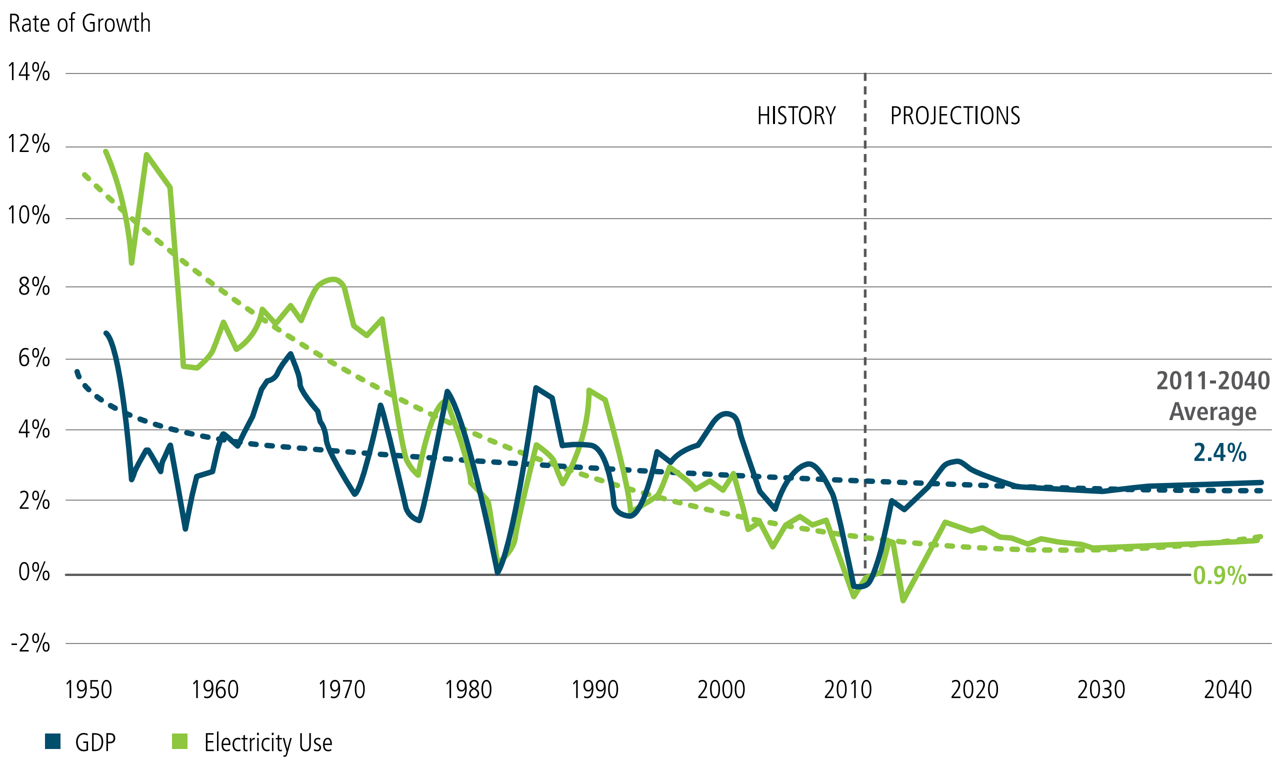
[c] Note that the EIA 2030 projection made does not include laws and policies not enacted or finalized at the time of the projection.

Natural gas-fired power plants accounted for just more than 50 percent of new utility-scale generating capacity added in 2013.[50, d] Natural gas-fired capacity continued to expand in 2014.[51] Infrastructure changes may be needed to accommodate future growth in natural gas use for power, including repurposing and reversals of existing pipelines; laterals[e] to gas-fired generators;[52] more looping and compression to the existing network; potential new pipelines (although, this could be regionalized); and additional processing plants and high-deliverability storage. Under multiple scenarios, the pace of these changes for the interstate natural gas pipeline system through 2030 is projected to be comparable to or less than historical build rates.

Slowing Rate of Electricity Demand Growth

Growth in U.S. electricity demand is at its lowest level in decades (as illustrated in Figure 1-2), driven most significantly by policies that promote energy efficiency, supply/demand balance, and the shift in the economy to less energy-intensive industry.[53] It is important to note, at the same time, that while there is low demand growth nationally, there is wide variation in the amount of load growth across states and regions (see Figure 1-3).

Figure 1-2. U.S. Electricity Use and Economic Growth (3-Year Compound Growth Rate), 1950–2040[54]



The rate of growth in electricity use has declined since 1950, while the rate of growth in gross domestic product has stayed relatively constant. The slower electricity growth rate is a result of several factors, including a decline in energy-intensive industries, increasing energy efficiency, and the slow recovery from the recent recession.

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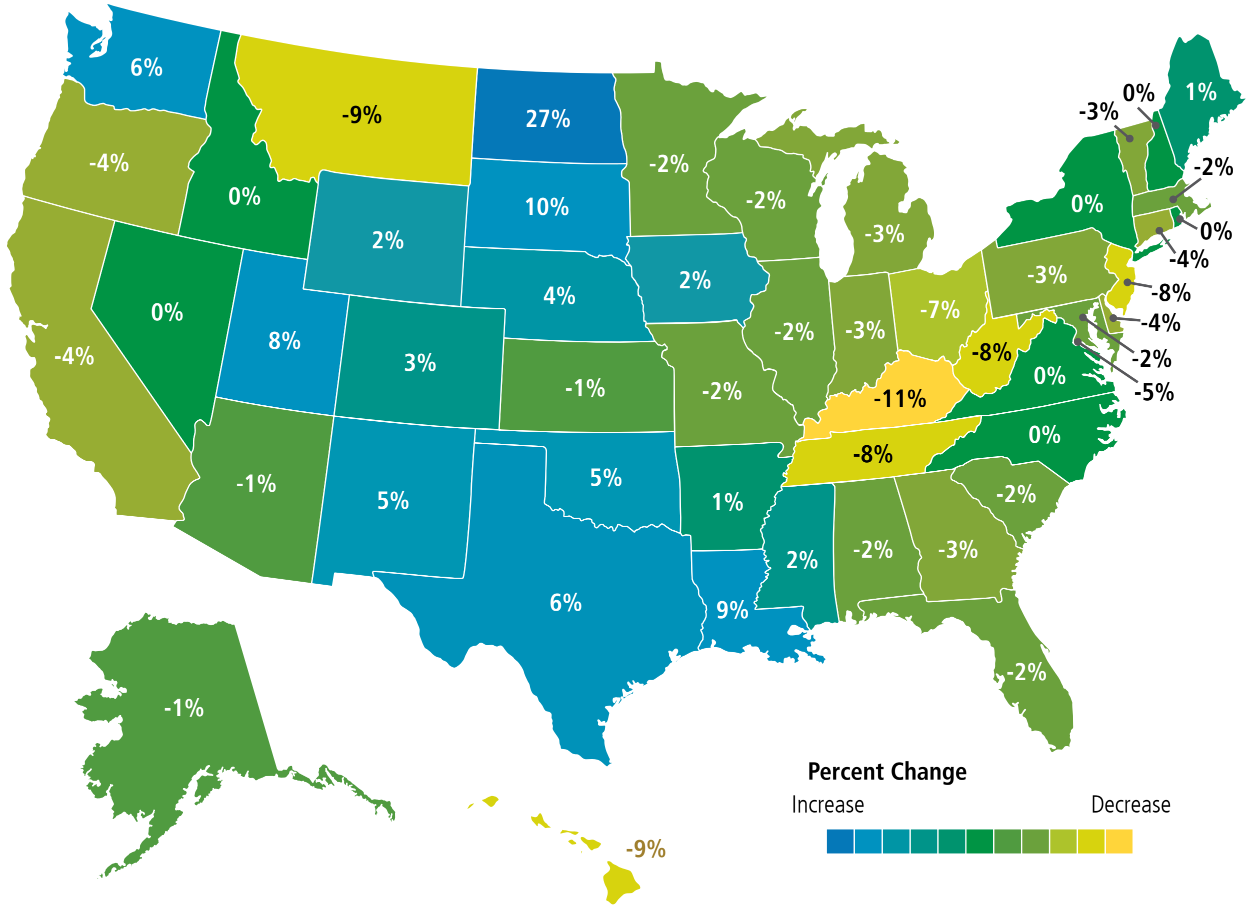
[d] Representative capacity factors by technology are: coal 85 percent, conventional combined cycle 87 percent, conventional combustion turbine 80 percent, nuclear 90 percent, wind 35 percent, solar photovoltaic 25 percent.

[e] Small segments of pipelines designed to link gas-fired power plants to the natural gas pipeline system.

Figure 1-3. Percent Change in Retail Electricity Sales (kilowatt-hours), 2008–2013[55]



There is a considerable variation in electricity retail sales among states and by region, ranging from an increase of 27 percent in North Dakota to a decrease of 11 percent in Kentucky; these variations are due in part to changes in load growth.

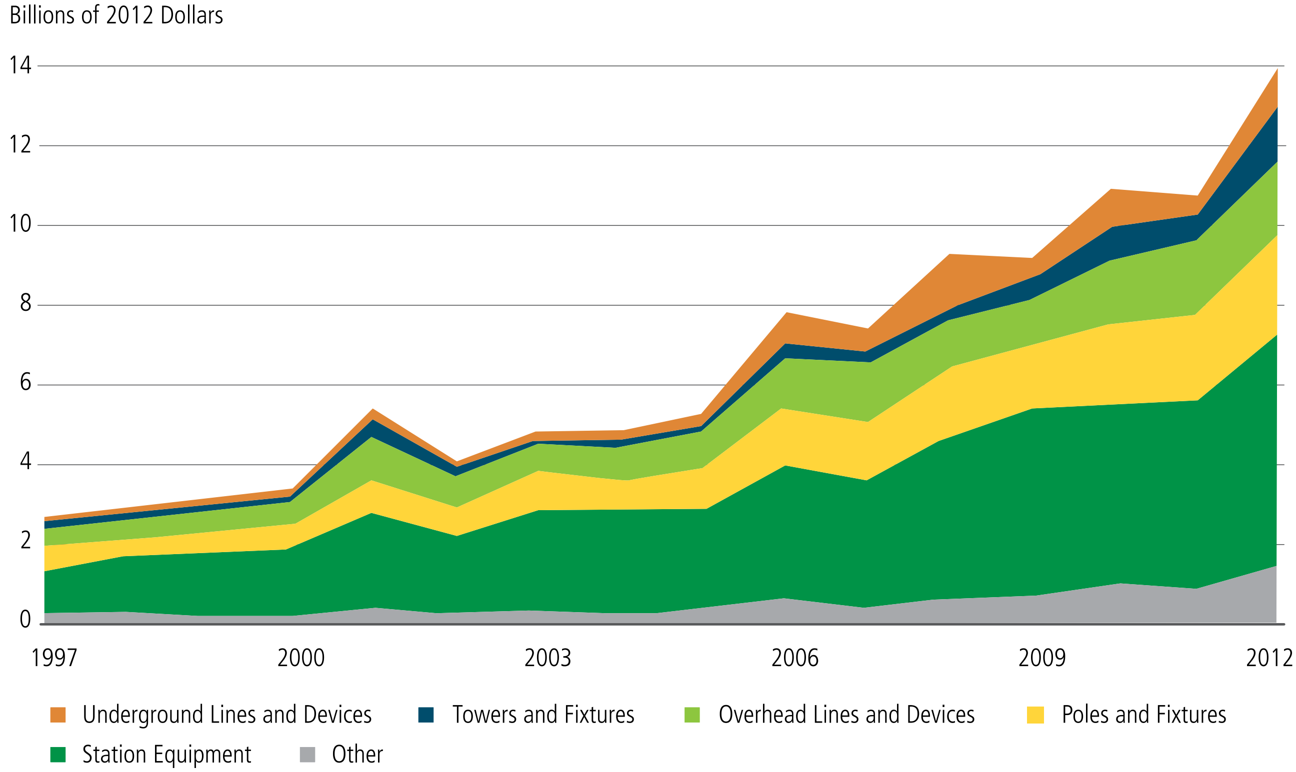
Power Plant Retirements

Since October 2012, utilities have announced the retirement of five nuclear reactors in California, Wisconsin, Florida, and Vermont; Oyster Creek in New Jersey is also slated for retirement.[56] U.S. electricity providers are announcing the retirement of a number of coal-generating assets. EIA forecasts 49.4 gigawatts of retirements between 2013 and 2020.[57] Changes in baseload generation will affect transmission infrastructure needs. Market-related factors driving coal retirements include declining growth in electricity demand, lower natural gas prices, and changing coal prices. Due to rising international demand and declines in domestic mining productivity, EIA projects steady price increases for coal through 2040;[58] meanwhile, market prices for coal have increased by roughly 70 percent since 2000.[59] Coal generation retirements will vary by region, based on the amount of existing coal generation, with regionally varying implications for transmission and bulk power system's operations and reliability. Retirements are also affecting the nuclear power industry, with closures announced in 2012–2013 of five nuclear reactors, the first since 1998. Nuclear power supplied nearly 19.0 percent of U.S. electricity in 2013—all of it carbon free—yet only accounts for 10.0 percent of total installed capacity, with 2014 preliminary data showing a record average 90.9 percent capacity factor for the Nation's 100 nuclear units.[60] The loss of these plants could lead to a shift in power flows across the transmission system.

Rising Investment in Electric Transmission

According to EIA, between 1997 and 2012 electric transmission investments by private companies and investors increased fivefold in real terms (2012 dollars), growing from $2.7 billion in 1997 to $14.1 billion in 2012—reversing a three-decade decline (see Figure 1-4).[61] Reasons for increased investment include reliability enhancement, connecting to renewables, demand shifts, cost increases, and market reforms that created more options for independent generators.

Figure 1-4 Investment in Transmission Infrastructure by Investor-Owned Utilities, 1997–2012[62]



Spending on transmission Infrastructure has increased fivefold since the late 1990s.

Climate Change

Energy TS&D infrastructure has always been shaped not only by the mix of energy supply technologies and end-use patterns, but also by the characteristics of the environment where the infrastructure must operate, including, for example, terrain, vegetation, soil and seismic conditions, and climate. It has long been true, as well, that choices about TS&D infrastructure have had to take into account the need to limit that infrastructure's adverse impacts on the environment.

By far the most important environmental factor affecting TS&D infrastructure needs now and going forward is global climate change. Sea-level rise, thawing permafrost, and increases in weather extremes are already affecting TS&D infrastructure in many regions. The need to mitigate global climate change by reducing GHG emissions, moreover, is accelerating changes in the mix of energy supply options and end-use patterns, and over time, it is likely to become the dominant such influence. Reducing GHG emissions from TS&D infrastructure, including methane emissions from the transmission and distribution of natural gas, will be increasingly important in this context.

Some key aspects of the climate change picture are summarized here as a prelude to the discussion in later chapters of how decisions about TS&D infrastructure will likely be influenced by this and other environmental issues.

Climate Science

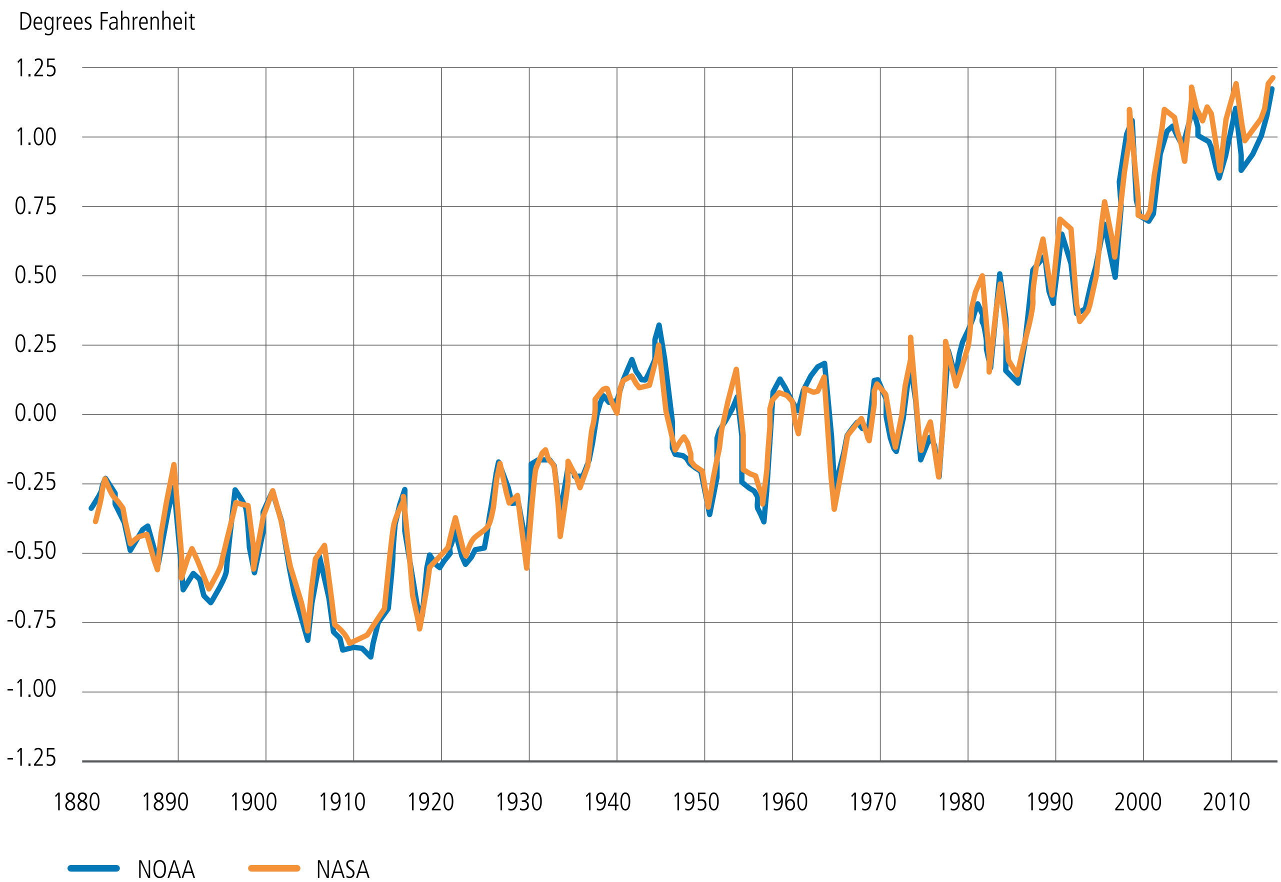
The key conclusions from climate science—as embodied in the most recent reports of the Intergovernmental Panel on Climate Change,[63] the National Academy of Sciences (jointly with the Royal Society of London),[64] and the Third National Climate Assessment of the U.S. Global Change Research Program[65]—are that GHGs emitted by civilization's energy system are the dominant cause of changes in climate being observed across the globe; that the changes not just in average conditions but in extremes are already causing harm to life, health, property, economies, and ecosystem processes; and that deep reductions in GHG emissions will be required if an unmanageable degree of global climate change is to be avoided.

Climate Trends

The annually and globally averaged air temperature near Earth's surface has been directly computable from thermometer measurements around the world since the late 19th century; determinations of this average over the period 1880–2014 by the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration are shown in Figure 1-5. According to the best estimates of both organizations, 2014 was the hottest year since 1880, 2010 the second hottest, and 2005 the third hottest.

The increase in the average temperature, amounting to about 1.4 degrees Fahrenheit for the world and 1.6 degrees Fahrenheit for the United States, is not *per se* the essence of the climate change problem, however. These average temperatures, like the temperature of the human body, are simply indices pointing to the overall state of a very complex system. In the case of climate, the state of the system includes not just the averages, but the spatial and temporal variations of temperature, humidity, clouds, winds, rainfall and snowfall, and tropical and extratropical storminess, as well as such closely related factors as sea level; sea-ice cover; ocean currents; the stability of permafrost; and the amount of water stored in groundwater, snowpack, and mountain glaciers.

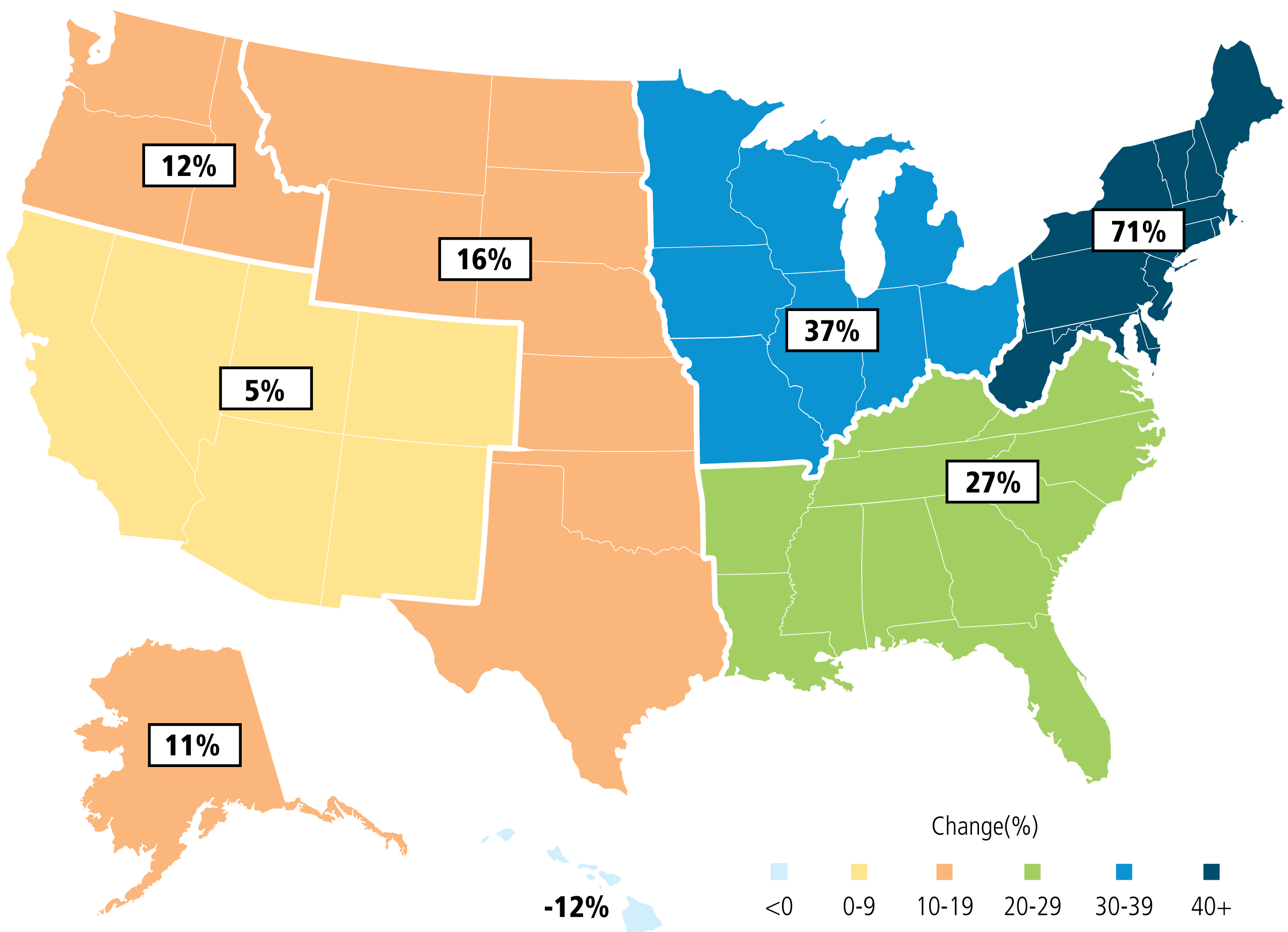
Figure 1-5. Global Average Surface Air Temperature Relative to the 1951–1980 Average[66]



Climate Change Impacts

A number of the manifestations of global climate change are particularly relevant to the TS&D focus of this report. These include dramatic increases in very hot days and heat waves in many regions; a higher fraction of rain falling in downpours in most regions (see Figure 1-6); increases in the intensity of droughts, wildfires, and the most powerful storms in some; the shrinkage of sea ice and the thawing of permafrost in the far North; and the rise of mean sea level.

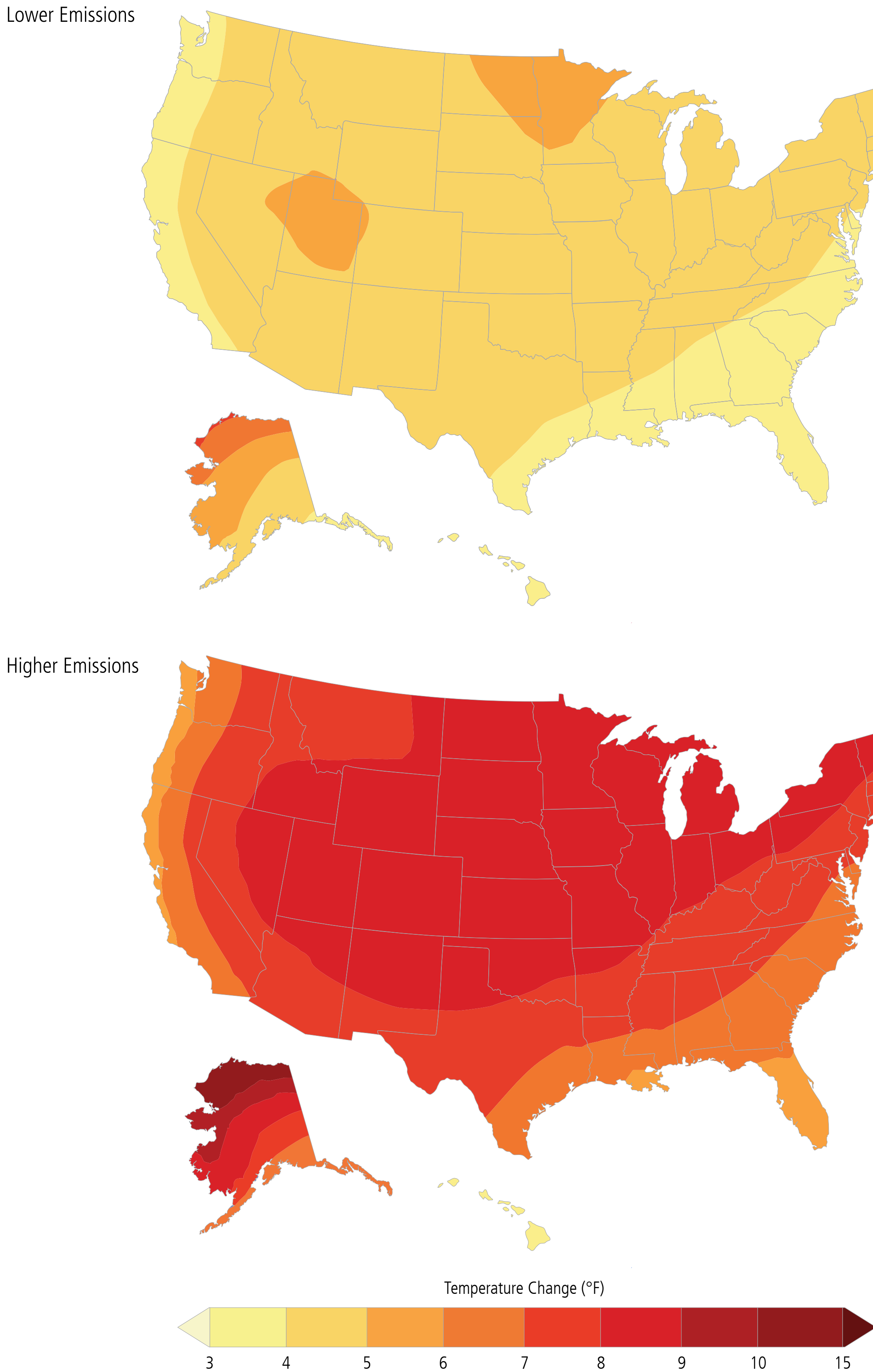
Figure 1-6. Observed Change in Very Heavy Precipitation[67]



Intense precipitation events are becoming more frequent, particularly in the northeastern United States. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1 percent of all daily events) from 1958 to 2012 for each region of the United States.

It is these kinds of changes that have brought climate change home to a large proportion of the world's population, including in the United States. Additionally, because of these manifestations of climate change beyond average warming, their impacts on life and property and livelihoods, and the prospect of their continuing to worsen going forward, in proportion to the size of future emissions (see Figure 1-7), that many policymakers, many leaders of business and civil society, and large majorities of publics around the world have concluded that it is time to take action both to reduce those emissions and to increase preparedness for and resilience against whatever further changes in climate materialize.

Figure 1-7. Change in Average Temperature in the Later Part of this Century (2071-2099; 20-year average) Relative to the Late Part of Last Century (1970-1999) under Low- and High-Emission Scenarios for Global GHGs[68]



Human Causes of Climate Change

The most important of the anthropogenic emissions driving global climate change are those of CO_2, methane, and particulate black carbon. Of the total warming influences exerted by anthropogenic emissions since the nominal start of the Industrial Revolution in 1750, 42 percent came from CO_2 emissions, 24 percent from methane emissions, and 16 percent from particulate black carbon emissions; the remainder was divided almost equally among emissions of halocarbons, nitrous oxide, and carbon monoxide (which converts to CO_2 in the atmosphere).[69] The relative importance of CO_2 emissions compared to those of the other heat-trapping substances has been growing over time, moreover. Based on integrated warming influence over the next 100 years, U.S. emissions of CO_2 in 2013 accounted for more than 82 percent of the impact of all U.S. GHG emissions combined for that year.[70] The share of CO_2 as a proportion of all global GHG emissions in the same year, calculated on the same basis, was about the same.[71]

The main sources of the anthropogenic additions of CO_2 to the atmosphere over the course of the industrial revolution have been fossil fuel burning (including flaring of natural gas), cement production, and land-use change. By 2013, the fossil fuel and cement contribution accounted for 92 percent of the total.[72] U.S. CO_2 emissions from fossil fuels and cement in 2013 amounted to about 17 percent of the world total and came from oil burning (40 percent), coal burning (30 percent), useful natural gas burning (25 percent), non-energy uses of fossil fuels (3 percent), cement manufacturing and other non-fossil-fuel industrial activities (1 percent), and gas flaring (1 percent).[73]

In recent years, the main contributors to global emissions of methane from human activities have been the fossil fuel system (30 percent of human-caused emissions), livestock (27 percent), landfills (21 percent), biomass/biofuels burning (11 percent), and rice cultivation (11 percent).[74] In the United States, which accounts for about 8 percent of anthropogenic methane emissions worldwide, the role of the energy system in methane emissions has been larger; the main contributors in 2013 were the fossil fuel system (43 percent), livestock and manure management (34 percent), and landfills and other waste management (20 percent).[75]

TS&D systems are responsible for only a small fraction of overall U.S. emissions. There are nonetheless opportunities to reduce emissions from this sector—for example, through halting methane leakage from natural gas pipelines and processing facilities. And, of course, the expanded implementation of no- and low-CO_2 energy technologies being undertaken to reduce the energy system's GHG emissions overall will place additional demands on TS&D in some cases (e.g., to link remote renewable energy sources with demand centers and to move captured CO_2 from fossil-fueled (and, possibly biomass-fueled) power plants through pipeline networks to sites for productive use or geologic storage).

The U.S. Response to the Climate Change Challenge

The Obama Administration has addressed the growing threat from climate change through a comprehensive set of energy and environmental strategies to cut GHG emissions domestically and through sustained diplomacy to spur global action.

The Administration's First Term

First term actions include $80 billion of investments in a cleaner, more efficient U.S. energy future through the American Recovery and Reinvestment Act of 2009, as well as additional funding through subsequent Presidential budgets; the promulgation of the first-ever joint fuel economy/GHG emission standards for light-duty vehicles and new, more stringent energy efficiency standards for commercial and residential appliances; and the announcement of a U.S. emissions reduction target in the range of 17 percent below the 2005 level by 2020.

Other actions to deploy low-carbon solutions included creation of the TIGER program (i.e., the Transportation Investment Generating Economic Recovery program), which combines Federal, private, state, and local funding to advance public transportation; the public-private Better Buildings Initiative to boost the energy efficiency of commercial and industrial buildings; and promulgation of the first-ever national fuel efficiency and GHG emissions standards for heavy-duty trucks and buses.

The Administration also invested in clean energy technology leadership through increases in DOE funding for research and development on clean energy and energy efficiency; creation of five Energy Innovation Hubs linking academia, industry, and government in a concerted effort to overcome barriers to the development and commercialization of a variety of cleaner and more efficient energy technologies; and the launch of the Transportation Electrification Initiative to accelerate market adoption of advanced electric vehicles.

These domestic initiatives contributed to a number of the trends affecting TS&D infrastructure that were mentioned previously in this chapter, such as decreases in oil consumption, increased deployment of renewable energy for power generation, and slowing the rate of electricity demand growth.

The Climate Action Plan

In June 2013, the President announced a comprehensive "Climate Action Plan," with three pillars:[76]

- **Additional measures to reduce domestic GHG emissions and bolster land-sector carbon sinks**, including CO_2 emission standards for existing and new fossil-fueled electric power plants, an interagency strategy to reduce methane emissions, and further commitments to clean energy and increased energy efficiency.
- **Measures to increase domestic preparedness for and resilience against changes in climate that can no longer be avoided**, including directing Federal agencies to incorporate climate change preparedness and resilience into their missions and policies, establishing interagency and state/local/tribal task forces on preparedness and resilience to advise on and implement additional steps, developing strategies and partnerships for managing floods and droughts, and mobilizing science and data to support these efforts.
- **Leading international efforts to address climate change**, including not just leading by example, but also bilateral and multilateral engagement on emission reduction targets and technologies (focusing particularly on the largest-emitting nations), assistance on building preparedness and resilience (focusing particularly on developing countries), and mobilizing clean energy and preparedness finance.

As noted in the Preface, the "Climate Action Plan" also mandated the production of an interagency QER, of which this report is the first installment.

Among the actions subsequently taken under the "Climate Action Plan,"[77] those with the greatest potential relevance for the future of TS&D infrastructure (and thus most germane to the focus of this report) include the following:

- **On domestic emissions**, changes to TS&D infrastructure will play a role in achieving the interagency strategy to reduce methane emissions nationwide, in the acceleration of permitting for new renewable energy projects on public lands and military installations, and in the implementation of Executive Orders requiring that Federal departments and agencies—including those with responsibilities relating to TS&D infrastructure—take climate change into account in all of their policies and programs.
- **On preparedness and resilience**, an Executive Order in November 2013 established both an interagency Council on Climate Preparedness and Resilience to coordinate the Federal Government's activities in this domain and a State, Local, and Tribal Leaders Task Force on Climate Preparedness and Resilience to advise the President and the council on needs on the ground. A climate data initiative was

launched in March 2014 to make available, in convenient form, all of the relevant data held by Federal departments and agencies; the "Third U.S. National Climate Assessment" (providing information tailored to regional and sectoral preparedness and resilience needs, including the needs of the energy sector) was released in May 2014, and the first version of a user-friendly U.S. Climate Resilience Toolkit was released to the public in November 2014. Among the benefits of these initiatives is better data and insight for TS&D infrastructure owners, regulators, and other stakeholders concerning the potential effects on that infrastructure of climate-driven phenomena such as sea-level rise.

- **On international engagement**, in November 2014, in a joint announcement with Chinese President Xi, President Obama announced a new U.S. target for post-2020 GHG emission reductions: 26 percent to 28 percent below 2005 levels by 2025. At that event, the Chinese government made the unprecedented commitment that Chinese emissions would peak by around 2030 and that China would boost its economy-wide share of non-fossil-fuel energy to about 20 percent by that time. Since then, the United States has worked with other countries, including Mexico, to secure ambitious climate change and clean energy commitments from those two countries, as well. Improvements to TS&D infrastructure will play a role in facilitating the achievement of the U.S. target and in increasing clean energy trade and market integration with Mexico.

Results of the Administration's Energy and Climate Policies

Between 2008 and 2014, the U.S. economy grew by 8.5 percent while total energy use and electricity generation both fell by 0.6 percent. That means the energy efficiency and electricity efficiency of the U.S. economy—real gross domestic product per quadrillion British thermal unit of total energy and real gross domestic product per billion kilowatt-hours of electricity—both grew during this period by 9.1 percent, an average of about 1.5 percent per year.[78] U.S. GHG emissions in 2013 were 7.0 percent below the 2008 level and 9.2 percent below the 2005 level used as a reference point for U.S. emissions reduction targets.[79]

A large part of these recent emissions reductions have come from the electric power sector, where emissions from coal burning declined 21.3 percent and emissions from all fossil fuel combustion in power plants declined 15.4 percent between 2005 and 2014.[80] Key factors contributing to this trend have included a reduction in demand growth; fuel switching from coal and petroleum to lower-carbon natural gas; and the previously mentioned growth in generation from wind and solar energy.[81] In addition, a combination of state and Federal policies, plus industry actions that include improved gas infrastructure equipment, contributed to a 13 percent decline in methane emissions in natural gas systems between 2005 and 2012.[82]

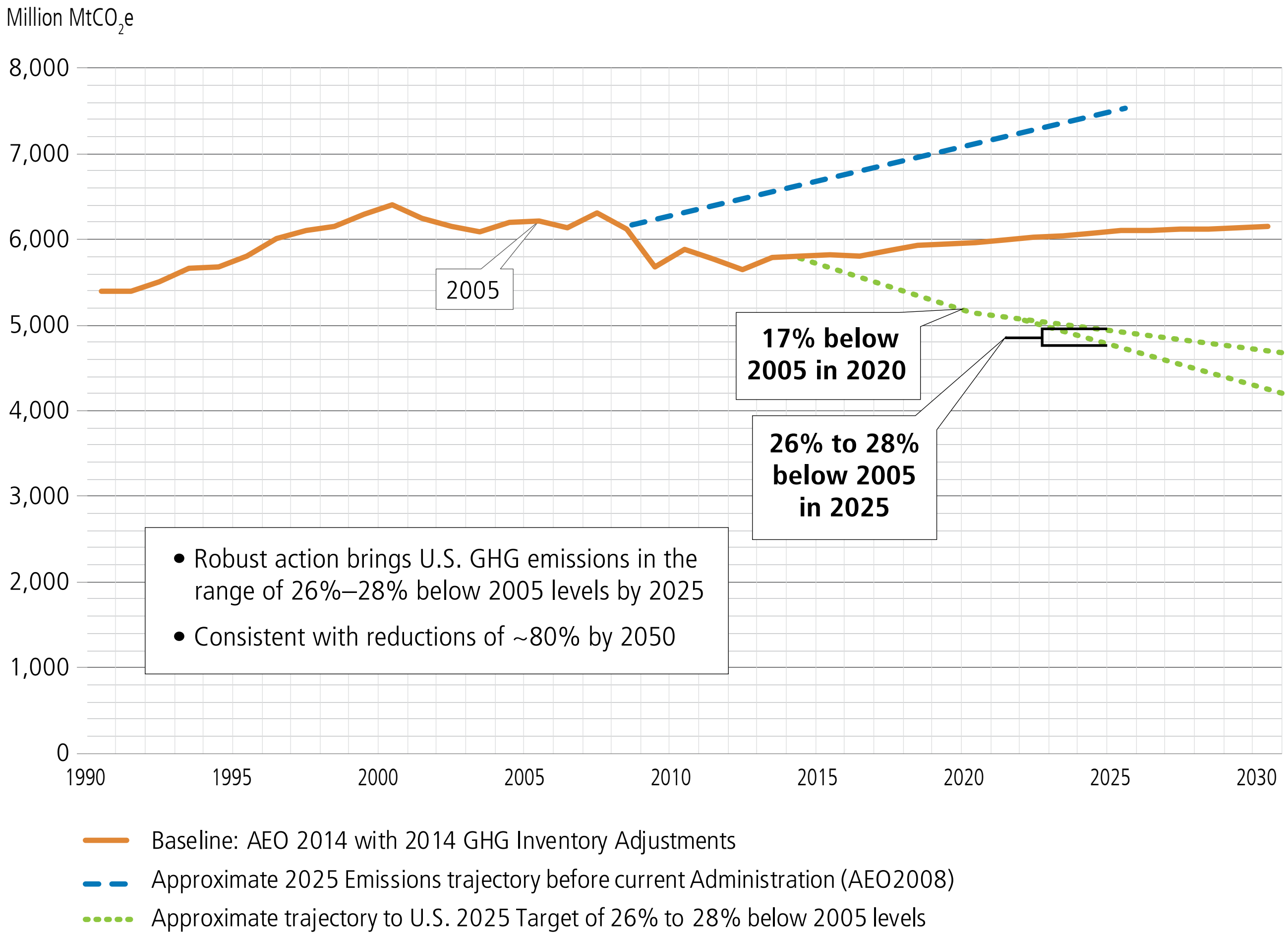
The Path Forward

As noted above, the Obama Administration committed formally in 2009 to a target of reducing U.S. GHG emissions to a level in the range of 17 percent below the 2005 value by 2020, and it committed further, in November 2014, to a level 26 percent to 28 percent below the 2005 value by 2025. Historic and projected U.S. emissions under these targets, to 2025, are shown in Figure 1-8.

The Administration's actions under the "Climate Action Plan" put the United States on a path to meet the Administration's 2020 and 2025 targets. According to the "U.S. Climate Action Report 2014" submitted by the Administration to the UN Framework Convention on Climate Change, U.S. emissions reductions by 2020 under the "Climate Action Plan," compared a 2012 Policy Baseline scenario,[f] could amount to 485 million metric tons to 800 million metric tons in energy sector CO_2, 100 million metric tons to 135 million metric tons of CO_2 equivalent in hydrofluorocarbons reductions under the Montreal Protocol, and 25 million metric

[f] The 2012 Policy Baseline Scenario assumes no additional measures beyond those in place in 2012 are implemented.

Figure 1-8. Historic and Projected U.S. GHG Emissions under Obama Administration Targets[83]



tons to 90 million metric tons of CO_2 equivalent in methane reductions under the "Climate Action Plan's" Methane Strategy.[84] The report indicates that these and a combination of smaller reductions from other sectors of the economy would bring total U.S. emissions in 2020 down to the range of 17 percent below 2005 levels.

Steepening of the downward trend after 2020, as Figure 1-8 shows, will be required in order to reach the target of 26 percent to 28 percent below the 2005 level by 2025. This is to be accomplished through several means, including implementation of carbon emission standards for the power sector that will drive further shifts to low- and zero-carbon fuels, cleaner electricity generation technologies, and continuing improvements in end-use efficiency. Improvements in TS&D infrastructures will assist in meeting these goals. While the Administration's 2020 and 2025 targets are ambitious, it is clear that continued reduction in GHG emissions will be needed beyond 2025 in the United States and globally. These reductions will continue to drive significant changes in TS&D infrastructure in the longer term.

Energy Finance for TS&D Infrastructure

Significant investment by both the private and public sectors will be required to meet energy objectives and reduce vulnerabilities to disruptive events, but capital and cost of capital issues will be less challenging in the near term than regulatory or market structure barriers. Although most energy TS&D assets are privately or non-federally funded and owned, significant elements of the Nation's shared transport infrastructure, increasingly important for energy commodities, are federally funded and owned.

Private Sector Financing for Infrastructure

As an investment class, infrastructure generally is considered to be a long-term investment with relatively low risk, and most energy TS&D infrastructure projects fall into this category. Capital generally is available for projects that have a predictable revenue stream, have stable cash flows, and are based on proven technologies.[g, 85] These may include distribution infrastructure investments, where the rate base and rate of allowed return on investment have been established for the utility by the public service commission through the rate case process, or investments by a natural gas midstream pipeline company that have signed long-term contracts with suppliers or shippers. These stable, predictable returns are attractive to capital markets, including institutional investors, many of whom are looking for lower-risk, longer-duration assets to match long-dated liabilities.[86, h]

Barriers to investment tend to arise from unfavorable market fundamentals or regulatory challenges, rather than from constraints related to access or cost of capital (although, this may change if interest rates rise or risk spreads change). These barriers include lack of full market valuation (e.g., for grid ancillary services, including storage) and lack of information for decision makers (e.g., to inform an appropriate level of resiliency upgrades). Additionally, market externalities, such as climate change impacts due to GHG emissions, are not addressed. Additional public financing mechanisms may help support investment; for example, by de-risking projects that incorporate innovative technology, as well as ameliorating near-term affordability issues such as rate shock to customers from infrastructure modernization (further discussed in Chapter II, Increasing the Resilience, Reliability, Safety, and Asset Security of TS&D Infrastructure).

Public Sector Financing for Infrastructure

The Federal Government funds and owns key elements of the Nation's energy systems, such as the Strategic Petroleum Reserve for liquid fuels and the Power Marketing Administrations for electricity. The government also plays a role in demonstrating and deploying first-of-a-kind technologies at scale, such as through the DOE Loan Program. In addition, the Department of Agriculture's Rural Utility Service provides support for TS&D infrastructure. In addition, energy TS&D infrastructure investments have been supported by Federal tax credits and structures, such as master limited partnerships for natural gas and liquid fuels transmission, tax-exempt municipal bonds for public utilities, and investment tax credit for storage associated with renewable power.

Large segments of shared infrastructure, such as highways, water transportation, and ports, are supported by public funds.[87] For example, water transport infrastructure, including canals, shipping channels, and locks, are constructed and maintained by the Army Corps of Engineers through Federal appropriations. In many cases, as discussed in Chapter V (Improving Shared Transport Infrastructures), these assets serve a vital and increasing role in the transport and distribution of energy supplies, which have been underfunded for many years.

This installment of the QER and the analysis supporting its recommendations suggests the need for substantial additional private and public sector investment. Targeted Federal investments will be needed in areas such as the Strategic Petroleum Reserve, ports, and waterways, as well as other areas of traditional government responsibility, and to incentivize the mobilization of private sector capital. Appropriately designed Federal investments will pay significant dividends for the Nation's competitiveness, energy security, and the transition to a clean energy future. As disruptive events to energy infrastructure become more prevalent, the Federal

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[g] For example, one panelist at the QER Finance Stakeholder meeting in New York City commented that today's market has a "tremendous amount of capital" chasing "a dearth of [financeable] projects." See: Department of Energy. "Summary of Presentations and Comments at the Quadrennial Energy Review Stakeholder Meeting #13." p. 2. October 6, 2014.

[h] Additionally, global total capital for all mutual fund and institutional investors is estimated at approximately $75 trillion, with approximately $20 trillion in U.S. pension funds alone, although only a fraction of this capital is currently dedicated to the infrastructure asset class. See: Ceres. "Investing in the Clean Trillion: Closing The Clean Energy Investment Gap." www.ceres.org/resources/reports/investing-in-the-clean-trillion-closing-the-clean-energy-investment-gap/view.

Government can build and incentivize the capacity of states, tribes, and localities for greater reliability, resiliency, and recovery through energy assurance plans and grants.

Energy Infrastructure Data and Information

Policymakers and companies rely on energy data to understand the status and evolution of national energy systems and associated implications for markets, resilience, environment, safety, and other issues. One of the major goals of policymakers is to forecast potential trends or disruptions to the system, identify vulnerabilities, accurately characterize and quantify the scale of externalities, and then direct the response that is in the national interest. Good decision making by public and private entities alike on energy investments and policies requires accurate, accessible data and analysis. There are three overlapping areas around data that need to be improved in order for the Federal Government to accomplish its energy policy goals: data gaps, analytical methodology, and modeling/visualization tools.

Many national-level data gaps in liquid fuels, natural gas, and electricity infrastructure need to be filled, particularly for environmental and safety issues and energy-related transport. In many cases, current data is either outdated, sporadically collected, privately held, not coordinated in definitions or formats, "siloed" in different databases, or simply not collected. For example, information of railway congestion related to energy product transportation is severely outdated, with data often lagging by 2 years or more (see Chapter V, Improving Shared Transport Infrastructures).

Energy stakeholders also need improved, commonly accepted analytical methodologies to define, measure, verify, and evaluate options in order to make more accurate and timely decisions regarding infrastructure. For example, frameworks and tools for assessing energy infrastructure resilience to disruptions vary widely across industries and government agencies and may be well-tailored for specific industries and sectors, but are not designed to aid policymakers and regulators in understanding current vulnerabilities; in deciding where to focus efforts and investment to increase resilience; or in determining what level of resilience is needed to protect consumers, safety, and the economy.

Finally, as the quality and consistency of data improve, models available to the Federal Government must be adapted to utilize that data effectively and to address key emerging policy questions. For example, models cannot fully address issues of electric grid congestion at a national scale. Further, while many energy-sector-specific modeling and visualization tools already exist, these often are likely to ignore critical interdependencies or operate with low temporal resolution. Gaps also exist in high-quality modeling and visualization tools in specific subsectors, such as electricity distribution, natural gas production, bulk gas transmission, and the liquid fuels network.

TS&D Infrastructure Goals and Architecture of the Study

This report's integrated assessment of the emerging threats, risks, and opportunities for TS&D energy infrastructure in the United States was guided by three high-level goals:

Economic competitiveness: Energy infrastructure should enable the Nation to, under a level playing field and fair and transparent market conditions, produce goods and services that meet the test of international markets while simultaneously maintaining and expanding jobs and the incomes of the American people over the longer term. Energy infrastructures should enable new architectures to stimulate energy efficiency, new economic transactions, and new consumer services.

Environmental responsibility: Energy infrastructure systems should be developed and managed in an environmentally responsible manner, taking into consideration the imperatives of climate change and the societal costs and benefits of reducing or avoiding pollution and land-use impacts on a lifecycle basis in order to minimize their environmental footprint while enabling better environmental performance for the energy system more broadly. It is also important for policies to promote equity and avoid disproportionate impacts to any particular populations.

Energy security: Vulnerabilities resulting from disruptions to energy infrastructure should be minimized from disruptions in supply and mitigate impacts of disruptions, including economic impacts. If disrupted, the U.S. energy infrastructure should be able to recover quickly. Energy security should support overall national security and encompass a collective approach to U.S. allies, other friendly nations, and trading partners.

The "Desirable Infrastructure Characteristics" box provides a longer list of characteristics that U.S. TS&D infrastructures should embody (in varying degrees) by 2030. The overall structure of the study and its recommendations is depicted in Figure 1-9.

Desirable Infrastructure Characteristics

In addition to the high-level goals of competitiveness, energy security, and environmental responsibility, this report focuses on how to enhance a more granular set of desirable characteristics that transmission, storage, and distribution infrastructures should, in varying degrees, embody by 2030:

Reliability. The ability of a system or its components to operate within limits so that instability, uncontrolled events, or cascading failures do not result if there is a disturbance, whether the disturbance is a disruption from outside the system or an unanticipated failure of system elements. Reliability also means that a system's components are not unexpectedly failing under normal conditions.

Resilience. The ability of a system or its components to adapt to changing conditions and withstand and rapidly recover from disruptions. To the extent that actions improve a system's ability to withstand disruptions, they might be characterized as enhancing reliability, or resilience, or both. The ability to recover from a disturbance, however, is specific to resilience.

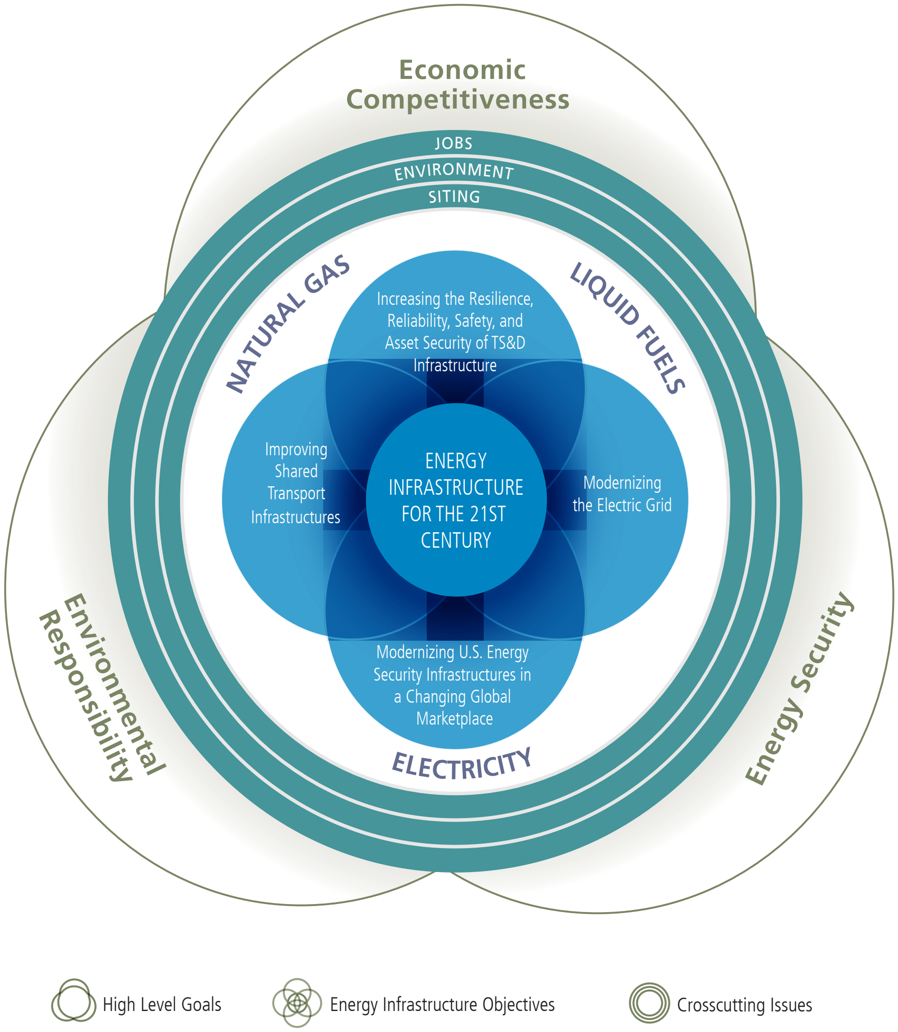
Safety. Achieving an acceptably low risk to life and health in the design, construction, operation, and decommissioning of a system. That level of risk is determined by taking into account the magnitude of potential consequences, the probability of those consequences occurring, and the costs of risk mitigation.

A minimal environmental footprint. Energy systems should be efficient and designed, constructed, operated, and decommissioned in a manner that minimizes carbon pollution. They should have a minimal impact on air quality and water quantity and quality, have a minimal land-use footprint, have a low impact on biological resources, and have minimal toxic emissions.

Flexibility. Energy infrastructure should be flexible enough to accommodate change in response to new, expected, or unexpected internal or external system drivers. Flexibility could include extensibility, the ability to extend into new capabilities beyond those required when the system first becomes operational; interoperability, the ability to interact and connect with a wide variety of systems and subsystems, both in and outside of the energy sector; and optionality, which provides infrastructures or features of infrastructures that would allow users to maximize value under future unforeseen circumstances. Distributed generation, for example, could include these characteristics.

Affordability. Ensures that at both the system and component levels, costs and defined needs (or requirements) of users are balanced with their ability to pay and consider the value created by the energy goods or services for the users or the system.

Figure 1-9. Objectives, Goals, and Organization of the QER[88]



This figure shows the comprehensive set of interactions and overlapping objectives and goals of energy TS&D infrastructure, and of the corresponding organization of the QER.

Figure Notes:

1. Analyses were conducted with high-level national goals as the guideposts: (1) energy security, (2) environmental responsibility, and (3) economic competitiveness.
2. Central to the QER is a set of four analytically derived objectives that represent an integrated approach to assessing the adequacy of our TS&D energy infrastructures for supporting these high-level goals. These objectives are: (1) increasing TS&D resilience, reliability, safety, and asset security; (2) modernizing the electric grid; (3) modernizing U.S. energy security infrastructure; and (4) improving shared transport infrastructures.
3. The QER also provides more conventional sector-level analyses of three infrastructures that represent key fuels/energy carriers: (1) liquid fuels, (2) natural gas, and (3) electricity. Each of these is described in detail in Appendices A, B, and C. Finally, the figure shows a host of additional crosscutting government and private sector mechanisms/tools that enable or impede energy infrastructures in achieving the objectives; these are represented in the surrounding circles and include jobs and training, environment, and siting. Other crosscutting issues are embedded in the integrated analysis.

Assessing Trends Using Scenario Analysis

The QER used scenario analyses to assess the impact of many of the factors previously described on the need for liquid fuels, natural gas, and electricity transmission infrastructure between 2014 and 2030. The scenarios explored infrastructure changes and TS&D investments that might be required under a range of possible future conditions, including changes in policy. Factors analyzed included, among others, an economy-wide cap on CO_2 emissions driving a 40-percent reduction in 2030, decreases in renewable generation costs, increased natural gas prices, and dramatic expansions of LNG export capacity (see Table 1-2). Each of these scenarios was run individually, and some were run in combination. The scenarios were defined to be "stressing" as they were not those considered most likely, but were those that might require the greatest amount of change in existing infrastructure. Each scenario was compared to the Annual Energy Outlook 2014 Reference case. Scenario outputs included the amount of additional transmission and storage infrastructure built, GHG emissions, and energy costs.

Table 1-2. QER Scenarios

Scenarios	Model
Base Case: Annual Energy Outlook 2014 Reference Case	
Natural Gas • High domestic gas demand • High world gas supply • High U.S. exports	**Deloitte (MarketPoint)** • Coupled gas infrastructure and electricity market models • Outputs include major pipeline capacity expansions and new pipeline builds
Electricity • Low wind cost • Low solar cost • Low-cost storage • High/low electricity demand • High natural gas prices • 40-percent economy-wide greenhouse gas reduction by 2030 • High penetration of distributed generation (photovoltaic) • High natural gas use • No new transmission	**National Renewable Energy Laboratory (Renewable Energy Deployment System, ReEDS)** • Electricity generation capacity expansion model • Outputs include transmission capacity expansion, generation, electricity costs, etc.
Liquid Fuels • Low/high oil resource • Revisit oil export ban/keep intact • Low oil demand	**Energy Policy Research Foundation, Inc. (Ponderosa Crude Flow Model)** • Pipeline flow and refinery model allocates domestic and foreign crude oil based on refinery demand and margin optimization **Oak Ridge National Laboratory/Jacobs Model** • Detailed refinery modeling (Jacobs) informs simplified refinery, crude distribution model (Oak Ridge)

The natural gas scenario analysis results indicated that even under conditions of high domestic gas demand or high U.S. gas exports, the amount of new gas transmission infrastructure needed is lower than or commensurate with historical build rates. More new infrastructure is needed for the high U.S. exports case than for the high domestic demand case because new pipelines would be needed, especially in the Gulf region. The electricity scenarios similarly showed that transmission needs through 2030 do not significantly exceed historical build rates under a wide range of renewable energy deployments, under a GHG cap, and under accelerated retirements. Certain scenarios do, however, produce different regional transmission needs; for example, more transmission is required in the Great Lakes region relative to the base case if wind costs drop by about 15 percent. Finally, liquid fuels scenarios showed that very little liquid fuels transmission infrastructure will be built even under high-demand conditions.

In parallel with the QER, DOE is conducting a Quadrennial Technology Review examining energy research, development, demonstration, and deployment opportunities. Unlike the QER, which assesses the entire energy sector, the QTR is more directly focused on DOE's internal research and technology priorities. The first QTR was issued in 2011, and the box below describes the 2015 QTR effort.

The Quadrennial Technology Review

The Quadrennial Technology Review (QTR) is a report issued by the Department of Energy (DOE) that examines the most promising research, development, demonstration, and deployment (RDD&D) opportunities across a broad spectrum of energy supply and end-use technologies. The first QTR was issued in 2011; DOE is anticipating the release of the second review in mid-2015. While the Quadrennial Energy Review (this report) is focused on infrastructure and policy issues across the public sector, the QTR is primarily focused on DOE-supported RDD&D to meet national energy challenges and goals. The two reviews are parallel to and complementary with each other.

The 2011 QTR defined a framework for understanding and discussing energy system challenges; established a set of priorities for DOE; and explained to stakeholders the roles of DOE and its national laboratories, the broader government, the private sector, academia, and innovation in energy transformation.

The 2015 edition of the QTR will describe the Nation's energy technology landscape and the dramatic changes that have taken place since the first report in 2011. The 2015 QTR will approach the analysis from a systems perspective to explore the integration of science and technology. It will include chapters on the following:

- Advancing systems and technologies to produce cleaner fuels
- Enabling modernization of electric power systems (grid)
- Advancing clean electric power technologies (generation)
- Increasing efficiency of building systems and technologies
- Innovating clean energy technologies in advanced manufacturing
- Advancing clean transportation and vehicle systems and technologies
- Enabling capabilities for energy science and technology.

As with the 2011 QTR, the 2015 QTR will inform DOE's strategic planning through detailed technology assessments that examine potential RDD&D pathways and their impacts out to 2030 and beyond.

More information on the QTR can be found at www.energy.gov/qtr.

Organization of the Remainder of the Report

The analysis conducted for the QER identified four major integrated objectives that address near-, mid-, and long-term energy infrastructure needs and challenges, which are covered in Chapters II through V:

- **Chapter II. Increasing the Resilience, Reliability, Safety, and Asset Security of TS&D Infrastructure**, focusing on the range of vulnerabilities and growing threats for TS&D infrastructures and ways to decrease those vulnerabilities, including hardening them to make them less vulnerable, more reliable and resilient, or safer.
- **Chapter III. Modernizing the Electric Grid**, enabled through infrastructures, policies, technologies, and other mechanisms.
- **Chapter IV. Modernizing U.S. Energy Security Infrastructures in a Changing Global Marketplace**, including physical, market, and geopolitical recommendations.
- **Chapter V. Improving Shared Transport Infrastructures**, focusing on rail, waterways, ports, and roadways—transportation modes shared by other commodities and products that are seeing significant increases in use for the transportation of energy commodities.

The report also focused on crosscutting areas of inquiry that are important to the integrated analyses, as well as the analyses of the physical energy infrastructures in Chapters VI through IX:

- **Chapter VI. Integrating North American Energy Markets** summarizes how an integration of the North American energy market could enhance energy security, reliability, resiliency, and competitiveness policies affecting cross-border infrastructures.
- **Chapter VII. Addressing Environmental Aspects of TS&D Infrastructure** focuses on ways to cut carbon pollution and protect the environment.
- **Chapter VIII. Enhancing Employment and Workforce Training** focuses on enhancing jobs, competitiveness, and training for modernizing energy infrastructures.
- **Chapter IX. Siting and Permitting of TS&D Infrastructure** focuses on promoting siting and permitting policies that expedite infrastructure build-out while protecting the environment and communities.

The processes through which the findings and recommendations emerged are described in:

- **Chapter X. Analytical and Stakeholder Process** describes how the QER analysis was informed by the stakeholder outreach effort and provides details on the systems analysis commissioned to support the QER.

Sector-specific analyses of the following physical infrastructures (listed in more detail in Table 1-1) were also completed and accompany this report as appendices, as does a summary of Federal emergency authorities germane to recovery of TS&D infrastructure after disasters:

- **Appendix A. Liquid Fuels**
- **Appendix B. Natural Gas**
- **Appendix C. Electricity**
- **Appendix D. Federal Emergency Authorities.**

Endnotes

1. Edison Electric Institute. "EEI Statistical Yearbook 2013." Table 10.6. http://www.eei.org/resourcesandmedia/products/Pages/ProductDetails.aspx?prod=617A7D67-9678-44FC-AE6F-6876ADAE7406&type=S. Accessed March 18, 2015.

2. Platts. "Platts UDI Directory of Electric Power Producers and Distributors, 122nd Edition of the Electrical World Directory." p. vi. 2014.

3. Department of Energy, Office of Energy Policy and Systems Analysis. 2015.

4. Department of Energy. "Grid 2030: A National Vision for Electricity's Second Hundred Years." 2003. http://www.ferc.gov/eventcalendar/files/20050608125055-grid-2030.pdf. Accessed January 26, 2015.

5. Edison Electric Institute. "Transforming America's Power Industry: The Investment Challenge 2010-2030." November 2008. http://www.eei.org/ourissues/finance/Documents/Transforming_Americas_Power_Industry_Exec_Summary.pdf. Accessed January 15, 2015.

6. Department of Transportation. "The State of the National Pipeline Infrastructure." p. 7. 2011. https://opsweb.phmsa.dot.gov/pipelineforum/docs/Secretarys%20Infrastructure%20Report_Revised%20per%20PHC_103111.pdf.

7. Energy Information Administration. "Crude Oil Production." December 30, 2014. http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm. Accessed January 15, 2015.

8. Energy Information Administration. "U.S. Crude Oil and Natural Gas Proved Reserves: With data for 2013." December 4, 2014. http://www.eia.gov/naturalgas/crudeoilreserves/. Accessed February 2, 2015.

9. Energy Information Administration. "Crude Oil Proved Reserves, Reserves Changes, and Production." December 4, 2014. http://www.eia.gov/dnav/pet/pet_crd_pres_a_EPC0_R01_mmbbl_a.htm. Accessed February 2, 2015.

10. Energy Information Administration. "Natural Gas Summary." January 30, 2015. http://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm. Accessed February 2, 2015.

11. Energy Information Administration. "Natural Gas Summary." January 30, 2015. http://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm. Accessed February 25, 2015.

12. Energy Information Administration. "Natural Gas." http://www.eia.gov/dnav/ng/ng_enr_shalegas_dcu_NUS_a.htm. Accessed February 25, 2015.

13. Energy Information Administration. "Shale Gas." December 4, 2014. http://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm. Accessed February 2, 2015.

14. Energy Information Administration. "U.S. Crude Oil and Natural Gas Proved Reserves." December 4, 2014. http://www.eia.gov/naturalgas/crudeoilreserves/. Accessed January 15, 2015.

15. Energy information Administration. "U.S. Product Supplied of Finished Motor Gasoline." January 29, 2015. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mgfupus1&f=a. Accessed February 26, 2015.

16. Environmental Protection Agency. "News Release: U.S. Fuel Economy Researches All-Time High/Fuel Economy Gains For New Vehicles Continue Under President Obama's Clean Car Program." October 8, 2014. http://yosemite.epa.gov/opa/admpress.nsf/bd4379a92ceceeac8525735900400c27/87acb71855bed86585257d6b0052c584!OpenDocument. Accessed January 15, 2015.

17. The White House. "Obama Administration Finalizes Historic 54.5 MPG Fuel efficiency Standards." August 28, 2012. http://www.whitehouse.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic-545-mpg-fuel-efficiency-standard. Accessed February 2, 2015.

18. Natural Gas Intelligence. "NGV Market Holds 1Bcf/d Potential, Raymond James Says." Daily GPI. May 15, 2012. http://www.naturalgasintel.com/articles/89411-ngv-market-holds-1bcf-d-potential-raymond-james-says. Accessed April 18, 2015.

19. Energy Information Administration. "Annual Energy Outlook 2014: Market Trends: Liquid fuels." May 7, 2014. http://www.eia.gov/forecasts/aeo/MT_liquidfuels.cfm. Accessed January 15, 2015.

20. Energy Information Administration. "Biofuels Issues and Trends." October 2012. http://www.eia.gov/biofuels/issuestrends/pdf/bit.pdf. Accessed February 2, 2015.

21. Department of Transportation. "U.S. Highway Vehicle-Miles Traveled." February 2013. http://www.rita.dot.gov/bts/publications/multimodal_transportation_indicators/2013_02/system_performance/us_highway_vehicle_miles. Accessed January 15, 2015.

22. Department of Transportation, Federal Highway Administration. "Historical Monthly VMT Report." http://www.fhwa.dot.gov/policyinformation/travel_monitoring/historicvmt.cfm. Accessed February 2, 2015.

23. Energy Information Administration. "U.S. Net Imports of Crude Oil and Petroleum Products." January 29, 2015. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MTTNTUS2&f=M. Accessed February 26, 2015.

24. Energy Information Administration. "Petroleum & Other Liquids: U.S. Imports by Country of Origin." December 30, 2014. http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbbl_m.htm. Accessed January 15, 2015.

25. Energy Information Administration. "Petroleum Navigator." http://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbblpd_m.htm. Accessed March 4 2015.

26. Energy Information Administration. "Weekly Imports and Exports." February 25, 2015. http://www.eia.gov/dnav/pet/pet_move_wkly_dc_NUS-Z00_mbblpd_w.htm. Accessed February 26, 2015.

27. Energy Information Administration. "U.S. Exports of Crude Oil and Petroleum Products." January 29, 2015. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MTTEXUS1&f=M. Accessed February 26, 2015.

28. Energy Information Administration. "Petroleum & Other Liquids: Exports." December 30, 2014. http://www.eia.gov/dnav/pet/pet_move_exp_dc_nus-z00_mbblpd_m.htm. Accessed January 15, 2015.

29. Energy Information Administration. "Locations of U.S. Natural Gas Import and Export Points." 2009. http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/impex_list.html. Accessed February 2, 2015.

30. Energy Information Administration. "Workbook Contents." December 31, 2014. http://www.eia.gov/naturalgas/pipelines/EIA-StatetoStateCapacity.xls.

31. Energy Information Administration. "U.S. natural gas exports to Mexico reach record high in 2012." Today in Energy. March 13, 2013. http://www.eia.gov/todayinenergy/detail.cfm?id=10351. Accessed January 15, 2015.

32. Department of Energy, Office of Fossil Energy. "Natural Gas Imports and Exports Second Quarter Report 2014." p. 15. http://energy.gov/sites/prod/files/2014/10/f19/2nd14ng.pdf. Accessed January 15, 2015.

33. Congressional Budget Office. "The Economic and Budgetary Effects of Producing Oil and Natural Gas from Shale." p. 1. December 9, 2014. http://www.cbo.gov/sites/default/files/cbofiles/attachments/49815-Effects_of_Shale_Production.pdf. Accessed January 15, 2015.

34. Thompson, J. "Booming Shale Gas Production Drives Texas Petrochemical Surge." Federal Reserve Bank of Dallas. Fourth Quarter 2012. http://www.dallasfed.org/assets/documents/research/swe/2012/swe1204h.pdf. Accessed January 15, 2015.

35. Energy Information Administration. "Natural Gas Consumption by End Use – Industrial." December 31, 2014. http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_m.htm. Accessed January 15, 2015.

36. Energy Information Administration. "Annual Energy Outlook 2014." Table A2. April 2014. http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf. Accessed February 2, 2015.

37. Energy Information Administration. "Net generation for all sectors, annual." Electricity Data Browser. http://www.eia.gov/electricity/data/browser. Accessed February 2, 2015.

38. Energy Information Administration. "Net generation for all sectors, annual." Electricity Data Browser. http://www.eia.gov/electricity/data/browser. Accessed February 26, 2015.

39. Energy Information Administration. "Net generation for all sectors, annual." Electricity Data Browser. http://www.eia.gov/electricity/data/browser. Accessed February 2, 2015.

40. Energy Information Administration. "Electric Power Monthly, November 2014" and "Electric Power Monthly, February 2014." http://www.eia.gov/electricity/monthly/. Accessed February 2, 2015.

41. The White House. "Solar Progress Report: Advancing Toward a Clean Energy Future." May 2014. http://www.whitehouse.gov/sites/default/files/docs/progress_report--advancing_toward_clean_energy_future.pdf. Accessed January 21, 2015.

42. Department of Energy. "Progress Report: Advancing Solar Energy Across America." February 12, 2014. http://energy.gov/articles/progress-report-advancing-solar-energy-across-america#. Accessed February 2, 2015.

43. Center for Climate and Energy Solutions. "Renewable and Alternative Energy Portfolio Standards." http://www.c2es.org/us-states-regions/policy-maps/renewable-energy-standards. Accessed February 2, 2015.

44. Barbose, G. "Renewables Portfolio Standards in the United States: A Status Update." Lawrence Berkeley National Laboratory. September 2014. http://emp.lbl.gov/sites/all/files/2014%20RPS%20Summit_Barbose.pdf. Accessed February 2, 2015.

45. North Carolina Clean Energy Technology Center. "Database of State Incentives for Renewables & Efficiency (DSIRE)." http://www.dsireusa.org/. Accessed February 26, 2015.

46. Energy Information Administration. "Monthly Energy Review." Table 7.3b. p. 110. February 2015. http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_10.pdf. Accessed March 20, 2015.

47. Energy Information Administration. "2014 Annual Energy Outlook." Table 135. May 7, 2014. http://beta.eia.gov/forecasts/aeo/tables_ref.cfm. Accessed February 25, 2015.

48. Energy Information Administration. "Monthly Energy Review." Table 7.2a. p. 97. January 2015. http://www.eia.gov/totalenergy/data/monthly/archive/00351501.pdf. Accessed February 25, 2015.

49. Energy Information Administration. "U.S. Natural Gas Consumption by End-Use." http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm. Accessed March 4, 2015.

50. Energy Information Administration. "Half of power plant capacity additions in 2013 came from natural gas." Today in Energy. April 8, 2014. http://www.eia.gov/todayinenergy/detail.cfm?id=15751. Accessed January 21, 2015.

51. Energy Information Administration. "Natural gas, solar, and wind lead power plant capacity additions in first-half 2014." Today in Energy. September 9, 2014. http://www.eia.gov/todayinenergy/detail.cfm?id=17891. Accessed February 2, 2015.

52. Tobin, J. "Expansion and Change on the U.S. Natural Gas Pipeline Network 2002." Natural Gas Analysis Publications 2002. May 12, 2003. http://www.eia.gov/pub/oil_gas/natural_gas/feature_articles/2003/Pipenet03/pipenet03.html. Accessed January 15, 2015.

53. Energy Information Administration. "U.S. economy and electricity demand growth are linked, but relationship is changing." Today in Energy. March 22, 2013. http://www.eia.gov/todayinenergy/detail.cfm?id=10491. Accessed February 2, 2015.

54. Energy Information Administration. "Annual Energy Outlook 2013 Early Release." December 2012.

55. Energy Information Administration. "EIA Electricity Data Browser: retail electricity sales data." http://www.eia.gov/electricity/data/browser. Accessed January 9, 2014.

56. Energy Information Administration. "Lower power prices and high repair costs drive nuclear retirements." Today in Energy. July 2, 2013. http://www.eia.gov/todayinenergy/detail.cfm?id=11931. Accessed February 26, 2015.

57. Energy Information Administration. "Annual Energy Outlook 2014." May 7, 2014. www.eia.gov/forecasts/aeo. Accessed January 26, 2015.

58. Energy Information Administration. "Annual Energy Outlook 2014." May 2014. http://www.eia.gov/analysis/projection-data.cfm#annualproj. Accessed February 9. 2015.

59. Energy Information Administration. "Coal Data Browser." January 20, 2015. http://www.eia.gov/coal/data.cfm#prices. Accessed February 9, 2015.

60. Nuclear Energy Institute. "US Nuclear Power Plants Posted Record High Efficiency in 2014." January 22, 2015. http://www.nei.org/News-Media/Media-Room/News-Releases/US-Nuclear-Power-Plants-Posted-Record-High-Efficie.

61. Energy Information Administration. "Investment in electricity transmission infrastructure shows steady increase." Today in Energy. August 26, 2014. http://www.eia.gov/todayinenergy/detail.cfm?id=17711. Accessed January 26, 2015.

62. Energy Information Administration (based on Federal Energy Regulatory Commission Financial Reports, as accessed by Ventyx Velocity Suite). "Investment in electricity transmission infrastructure shows steady increase." Today in Energy. http://www.eia.gov/todayinenergy/detail.cfm?id=17711. August 24, 2014.

63. Intergovernmental Panel on Climate Change. "Climate Science 2014: Synthesis Report." http://www.ipcc.ch/.

64. National Academy of Sciences and Royal Society of London. "Climate Change: Evidence and Causes." 2014. http://nas-sites.org/americasclimatechoices/more-resources-on-climate-change/climate-change-evidence-and-causes/.

65. Global Change Research Program. "Climate Change Impacts in the United States: The Third U.S. National Climate Assessment." 2014. http://nca2014.globalchange.gov.

66. Schmidt, G. and T. Karl. "NOAA/NASA Annual Global Analysis for 2014." January 2015. http://www.ncdc.noaa.gov/sotc/briefings/201501.pdf.

67. Global Change Research Program. "U.S. National Climate Assessment." 2014. http://nca2014.globalchange.gov/downloads.

68. Global Change Research Program. "Climate Change Impacts in the United States." 2014.

69. Intergovernmental Panel on Climate Change. "Climate Science 2013: The Physical Science Basis." Ch. 8 Supplementary Material, Table 8.SM.6.

70. Environmental Protection Agency. "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2013." February 11, 2015. http://www.epa.gov/climatechange/pdfs/usinventoryreport/US-GHG-Inventory-2015-Main-Text.pdf.

71. World Meteorological Organization. "The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2013." September 9, 2014. http://library.wmo.int/opac/index.php?lvl=notice_display&id=16396.

72. Global Carbon Project. "Global Carbon Budget 2014." September 21, 2014. http://www.globalcarbonproject.org/carbonbudget/.

73. Environmental Protection Agency. "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2013." February 11, 2015. http://www.epa.gov/climatechange/pdfs/usinventoryreport/US-GHG-Inventory-2015-Main-Text.pdf.

74. Intergovernmental Panel on Climate Change. "Climate Science 2013: The Physical Science Basis." Table 6.8.

75. Environmental Protection Agency. "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2013." February 11, 2015. http://www.epa.gov/climatechange/pdfs/usinventoryreport/US-GHG-Inventory-2015-Main-Text.pdf.

76. Environmental Protection Agency. "Inventory of Greenhouse Gas Emissions and Sinks: 1990-2013." April 2015. http://www.epa.gov/climatechange.ghgemissions/usinventoryreport.html. Accessed April 20, 2015.

77. The White House. "President Obama's Climate Action Plan: Progress Report." June 2014. https://www.whitehouse.gov/sites/default/files/docs/cap_progress_report_update_062514_final.pdf.

78. Energy Information Administration. "Monthly Energy Review." March 2015. http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

79. Energy Information Administration. "Monthly Energy Review." March 2015. http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

80. Energy Information Administration. "Monthly Energy Review." March 2015. http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

81. Energy Information Administration. "U.S. Energy-Related Carbon Dioxide Emissions, 2013." October 21, 2014. http://www.eia.gov/environment/emissions/carbon/. Accessed January 26, 2015.

82. Environmental Protection Agency. "Inventory of Greenhouse Gas Emissions and Sinks: 1990-2012." Chapter 3. 2014. http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Chapter-3-Energy.pdf.

83. The White House. "We're taking action of climate change." March 31, 2015. https://medium.com/@Deese44/we-re-taking-action-on-climate-change-and-the-world-is-joining-us-2bf44a62b9b9.

84. Department of State. "U.S. Climate Action Report 2014: First Biennial Report of the United States of America." January 2014. http://www.state.gov/documents/organization/219039.pdf.

85. Bosworth, B. and S. Milusheva. "Innovations in U.S. Infrastructure Financing: An Evaluation." The Brookings Institution and the Nomura Foundation Conference on the Global Economy after the Tohoku Earthquake. 2011. http://www.nomurafoundation.or.jp/wordpress/wp-content/uploads/2014/09/20111107_Barry_Bosworth-Sveta_Milusheva_000.pdf. Accessed February 26, 2015.

86. Della Croce, R. and J. Yermo. "Institutional Investors and Infrastructure Financing." OECD Working Papers on Finance, Insurance and Private Pensions, No. 36. OECD Publishing. 2013. http://dx.doi.org/10.1787/5k3wh99xgc33-en. Accessed January 15, 2015.

87. Congressional Budget Office. "Issues and Options in Infrastructure Investment." May 2008. www.cbo.gov/sites/default/files/05-16-infrastructure.pdf. Accessed January 15, 2015.

88. Department of Energy, Office of Energy Policy and Systems Analysis. 2015.