



Twelve Economic Facts on Energy and Climate Change

The Hamilton Project and Energy Policy Institute at the University of Chicago



This document was authored by Diane Whitmore Schanzenbach, Ryan Nunn, Audrey Breitwieser, Megan Mumford, and Gregory Nantz at The Hamilton Project; and Michael Greenstone and Sam Ori at Energy Policy Institute at the University of Chicago.

THE HAMILTON PROJECT MISSION STATEMENT

The Hamilton Project seeks to advance America's promise of opportunity, prosperity, and growth. The Project's economic strategy reflects a judgment that long-term prosperity is best achieved by fostering economic growth and broad participation in that growth, by enhancing individual economic security, and by embracing a role for effective government in making needed public investments. We believe that today's increasingly competitive global economy requires public policy ideas commensurate with the challenges of the 21st century. Our strategy calls for combining increased public investments in key growth-enhancing areas, a secure social safety net, and fiscal discipline. In that framework, the Project puts forward innovative proposals from leading economic thinkers — based on credible evidence and experience, not ideology or doctrine — to introduce new and effective policy options into the national debate.

The Project is named after Alexander Hamilton, the nation's first treasury secretary, who laid the foundation for the modern American economy. Consistent with the guiding principles of the Project, Hamilton stood for sound fiscal policy, believed that broad-based opportunity for advancement would drive American economic growth, and recognized that “prudent aids and encouragements on the part of government” are necessary to enhance and guide market forces.



EPIC MISSION STATEMENT

The Energy Policy Institute at the University of Chicago (EPIC) is confronting the global energy challenge by working to ensure that energy markets provide access to reliable, affordable energy, while limiting environmental and social damages. We do this using a unique interdisciplinary approach that translates robust, data-driven research into real-world impacts through strategic outreach and training for the next generation of global energy leaders.



Twelve Economic Facts on Energy and Climate Change

The Hamilton Project
Energy Policy Institute at the University of Chicago

Introduction

The United States is in the midst of an energy revolution. The North American shale boom has unlocked vast quantities of natural gas, upending domestic electricity markets and enabling rapidly growing export volumes. American shale oil has sent global oil prices to their lowest sustained level in a decade and slashed U.S. imports in half. Meanwhile, the cost of renewable fuels like wind and solar electricity has plummeted, and they now account for the majority of new electric generating capacity.

Given this technological and economic context, the United States has perhaps never been better positioned to tackle the urgent threat of climate change. Though it is often discussed as a future problem, climate change caused by greenhouse gas (GHG) emissions is happening now. The concentration of carbon dioxide (CO₂) in the atmosphere has increased from 317 parts per million in 1960 to more than 400 parts per million in 2016 (NOAA 2016), while the global average temperature has risen 1.6 degrees Fahrenheit (0.9° Celsius) above its 1960 level.

These changes are already impacting our everyday lives. Record-breaking temperatures, melting ice caps and more frequent coastal flooding, prolonged droughts, and damaging storms are just some of the intensifying risks we face as our planet continues to warm (IPCC 2007a). Despite these risks, the prices U.S. consumers pay for fossil fuels rarely reflect their costs, skewing consumption and investment choices away from cleaner fuels and discouraging the kinds of technological advancements that would allow the nation to make more efficient use of its energy resources.

On our current trajectory, climate change is expected to intensify over the coming decades. If no policy actions are taken to restrict GHG emissions, expected warming would be on track for 8.1°F (4.5°C) by 2100. Strikingly, this amount of warming is actually less than would be expected if all currently known fossil fuel resources were consumed. Were this to occur, total future warming would be 14.5°F (8°C), fueled largely by the world's vast coal resources.

The United States will not be insulated from a changing climate. If global emissions continue on their current path, average summer temperatures in 13 U.S. states and the District of Columbia would rise above 85°F (29.4°C) by the end of the 21st century, well above the 76 to 82°F (24 to 28°C) range experienced by these same states during the 1981–2010 period (Climate Prospectus n.d.). Climate change will lead to increased flooding, necessitating migration away from some low-lying areas; it will also lead to drought and heat-related damages (Ackerman and Stanton 2008).

There is no question that the United States has begun to make important progress on climate change. U.S. energy-related CO₂ emissions in 2016 were nearly 15 percent below their 2005 peak, marking the lowest level of emissions since 1992 (EIA 2017a). The drop was largely driven by recent reductions in the electric power sector, where inexpensive natural gas is displacing more carbon-intensive coal-fired generation and renewables like wind and solar are slowly gaining market share.

However, large challenges remain. Avoiding dangerous future climate change will require reductions in GHG emissions far greater than what have already been achieved. Though progress in reducing emissions associated with electric power provides cause for optimism, developments in other sectors are less encouraging. In particular, transportation recently surpassed electric power generation as the largest source of U.S. emissions and is projected to be a more important contributor in coming years. Transportation CO₂ emissions have increased despite strengthened fuel efficiency standards that aim to reduce emissions, suggesting that a review of this policy is warranted.

Moreover, climate change is a global problem. Recent gains in the United States have been offset by rising emissions elsewhere in the world. In past decades, most global emissions originated in the developed nations of Europe and North

America. However, new GHG emissions are increasingly generated by China, India, and other developing economies, where economic growth and improving living standards are highly dependent on access to reliable, affordable energy. Today, that largely means coal. As economic and population growth surges in these countries, GHG emissions will rise accordingly; as a result, global emissions will continue to rise despite stabilization in Europe and the United States.

Numerous technologies—from nuclear power and carbon capture and sequestration to cheaper renewables and energy storage—hold considerable promise for addressing the global climate challenge. Yet current economic conditions do not favor the large-scale implementation of these technologies in developed or developing countries. Rapidly deploying these solutions on a large scale would almost certainly require some combination of expanded research and development (R&D) investments and carbon pricing, the policy interventions recommended by economic theory.

It remains uncertain whether policy makers around the world will be successful in responding to the threat of climate change. The consensus view of the scientific community is that future warming should be limited to 3.6°F (2°C) (Jones, Sterman and Johnston 2016). Achieving that target would require much more dramatic actions than have been implemented globally, with global CO₂ emissions falling to near zero by 2100.

The Hamilton Project at the Brookings Institution and The Energy Policy Institute at the University of Chicago aim to support broadly shared economic growth. This jointly written document provides useful context for a discussion of the dangers to the economy posed by climate change and the policy tools for addressing those dangers. Given the immense threat that climate change represents, it is crucial that policy makers implement efficient solutions that minimize climate damages from our use of energy.

Table of Contents

INTRODUCTION	i
CHAPTER 1. The Energy and Climate Challenge	
1. The United States possesses ample affordable energy.	2
2. Global temperatures are rising.	3
3. Global temperatures would likely rise by another 14.5°F (8°C) if all remaining global fossil fuel resources were used.	4
4. China and India’s share of cumulative global GHG emissions is projected to grow substantially by 2100.	5
5. Over the next 70 years, every U.S. state is projected to experience increasing temperatures.	6
6. Much of U.S. infrastructure is vulnerable to the effects of climate change.	7
7. The prices we pay for fossil fuels do not reflect their social costs.	8
CHAPTER 2. Mitigation and Adaptation	
8. Electricity generation from renewable sources is expected to surpass generation from coal before 2050.	9
9. CO ₂ emissions from transportation now exceed electric power emissions.	10
10. Emissions from electric vehicles powered by coal plants are substantially higher than those powered by natural gas plants.	11
11. Public investment in energy R&D remains well below 1970s and 1980s levels.	12
12. Investments in climate adaptation would greatly lower the burden of climate change.	13
TECHNICAL APPENDIX	14
REFERENCES	15
RELEVANT PAPERS	18

1. The United States possesses ample affordable energy.

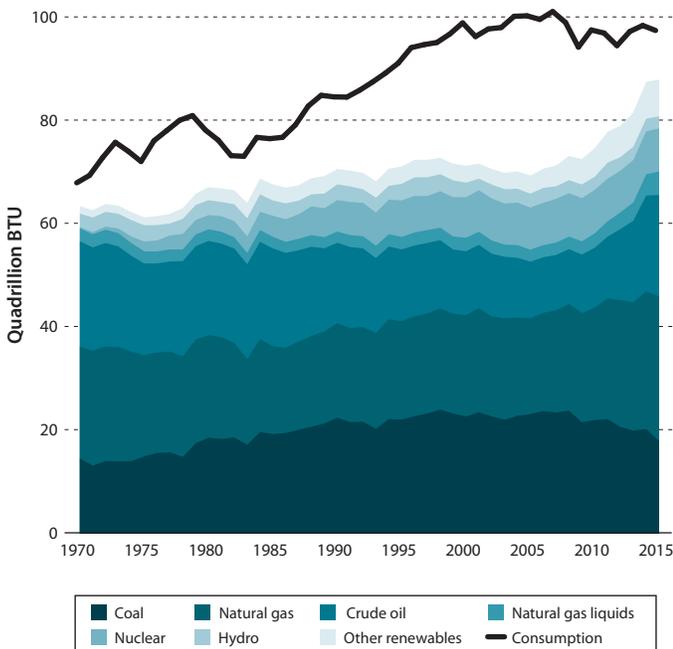
The United States is experiencing large increases in energy production, including both conventional fossil fuels and renewable sources. Driven by the advent of horizontal drilling and hydraulic fracturing, U.S. production of both natural gas and petroleum reached extremely high levels in 2015, with natural gas production even surpassing levels last reached in the 1970s (EIA 2017c). The surge in domestic production of both fuels has not only sharply reduced imports, but also created export opportunities that were widely unexpected as recently as a decade ago. U.S. liquefied natural gas (LNG) exports began in earnest in 2016, and surpassed 1 billion cubic feet per day by year-end (EIA n.d.a). Meanwhile, U.S. crude oil exports have surged following the elimination of statutory restrictions and averaged more than 500,000 barrels per day in 2016—though the nation remains a large net importer (EIA n.d.b).

Similarly, U.S. production of renewable fuels, including biomass and wind and solar electricity, has surged in recent years, growing by 55 percent since 2000. The fastest growth has occurred in the electricity sector, where wind production has grown 30-fold since 2000, and solar power by a factor of nearly seven. All told, U.S. domestic energy production reached a record 88 quadrillion BTU in 2015 compared to consumption of 97 quadrillion BTU. Total net imports supplied just 9.6 percent of consumption, down from a record 31 percent in 2005, suggesting that overall U.S. energy security has been significantly improved.

Combined with stable demand, the surge in domestic energy production has resulted in lower prices across multiple fuels, most notably oil and natural gas. The result is that American consumers are spending less on energy than at any time in decades. Measured as a share of GDP, consumer energy spending fell to 2.9 percent in 2015, its lowest level since 2002.

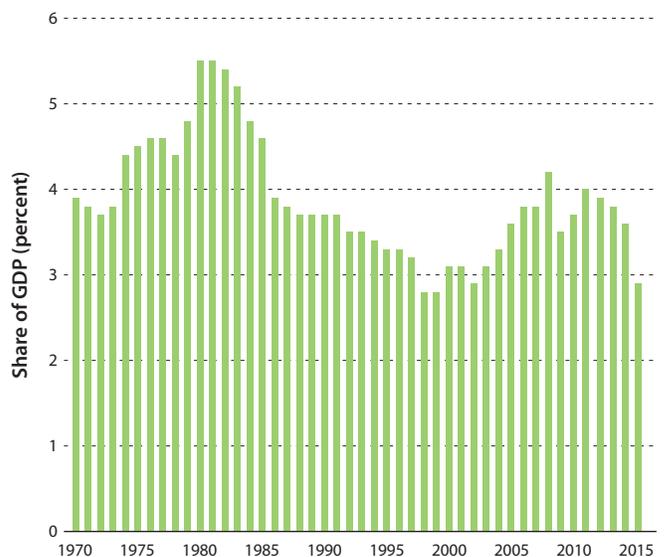
FIGURE 1A.
U.S. Energy Production by Fuel

Domestic energy production has surged since 2010, slashing prices and spending.



Source: EIA 2017c; BEA n.d.

FIGURE 1B.
U.S. Household Spending on Energy



2. Global temperatures are rising.

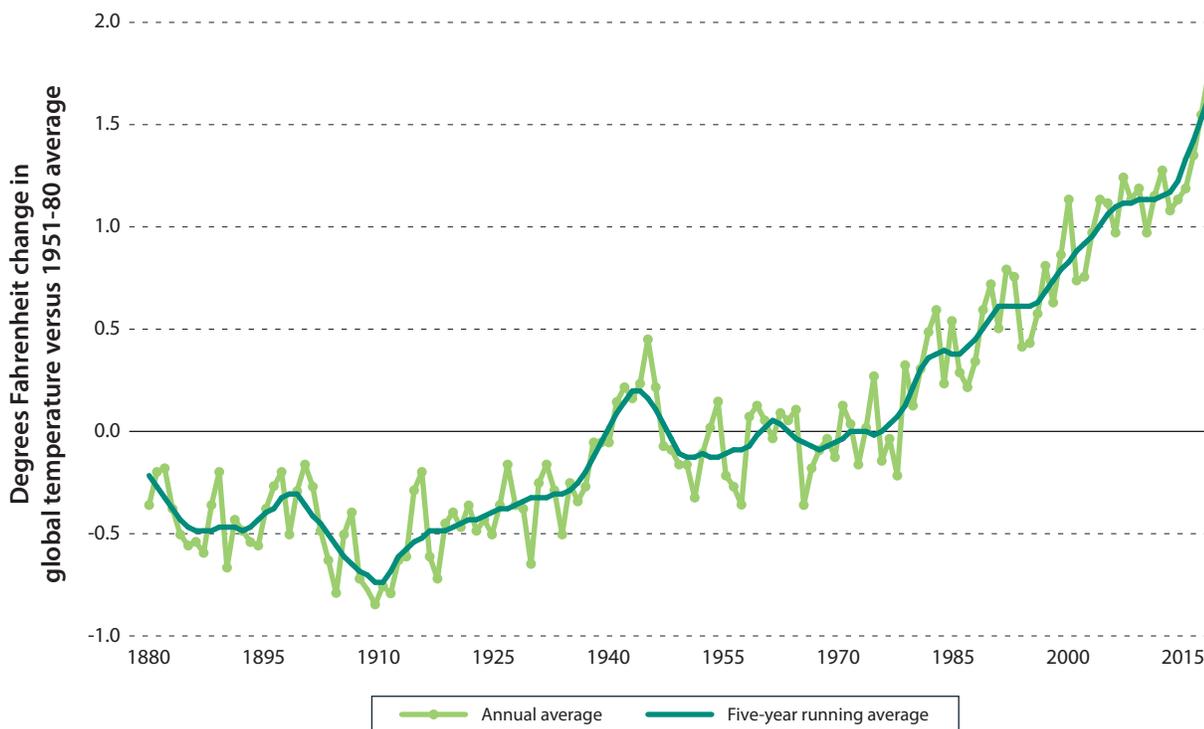
Discussions of climate change often give the impression that the phenomenon is exclusively about projections of the future—perhaps the distant future. However, climate change is already underway. The most straightforward evidence of climate change is the rising global average temperature. Indeed, “the 10 warmest years in the 134-year record all have occurred since 2000, with the exception of 1998” (GISS n.d). Using the 1951–80 period as a baseline, the current global average temperature is now elevated by 1.76°F (0.98°C). This increase has already had important effects on economies, infrastructure, and ecosystems. For example, exposure to high temperature conditions led to heat-related livestock losses exceeding \$1 billion nationwide in 2011, and premature budding due to a warm winter caused \$220 million in losses of Michigan cherries in 2012 (Hatfield et al. 2014).

Even this substantial temperature increase understates the extent of the departure from historical precedent. At 400 parts per million, atmospheric concentrations of CO₂ have reached levels not observed for 10 to 15 million years (Tripathi, Roberts, and Eagle 2009). As recently as 1960, the concentration was only 317 parts per million (NOAA 2016). CO₂ concentrations have in fact already reached the threshold that—over the long run—scientists believe will trigger disruptive climate change.

Unfortunately, CO₂ is removed from the atmosphere at a very slow rate. Even if policy actions were taken today to completely eliminate CO₂ emissions, the atmospheric CO₂ concentration would fall by only 40 parts per million over the entire 21st century (IPCC 2007b).

FIGURE 2.
Global Temperature Change, 1880–2015

Global temperature increase has accelerated in recent decades.



Source: Goddard Institute for Space Studies (GISS) n.d.

Note: Figure illustrates the change in global surface temperature (ocean and land) relative to 1951–80 average temperatures.

3. Global temperatures would likely rise by another 14.5°F (8°C) if all remaining global fossil fuel resources were used.

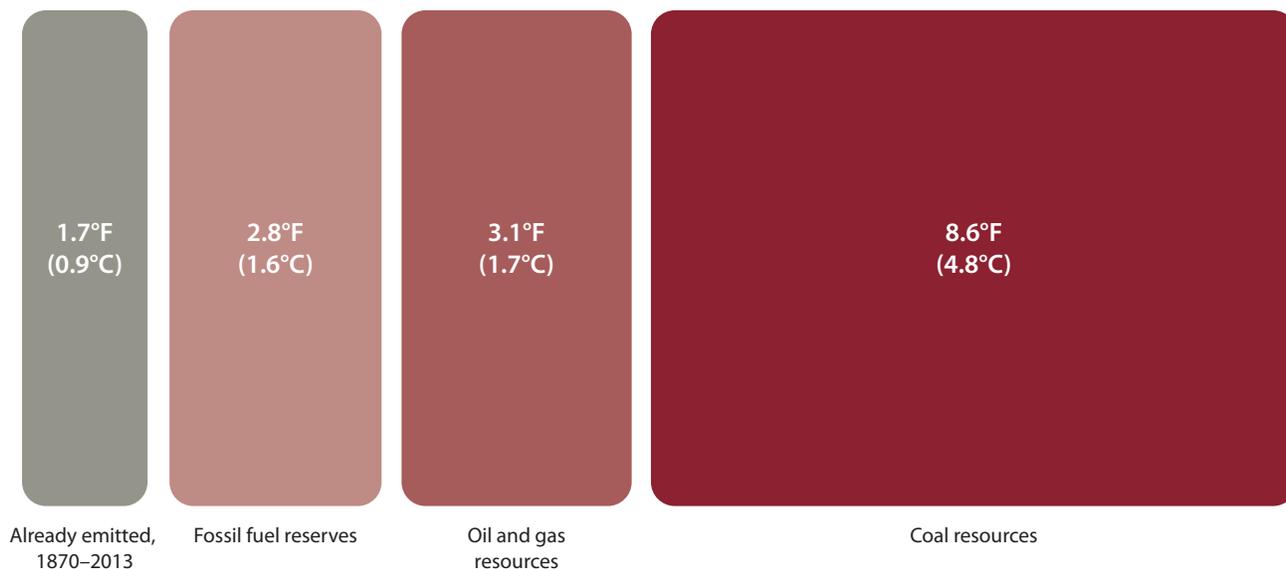
A common misconception about climate change is that the imminent exhaustion of fossil fuel resources will act as a natural restraint on CO₂ emissions and associated temperature rise. In fact, fossil fuel resources remain extensive, particularly in the form of coal: 985 billion tons of global reserves of coal have been identified (BGR 2015). New technologies, ranging from hydraulic fracturing techniques to improved offshore rigs, have made it possible and economically feasible to recover much more natural gas and oil than was previously possible, further expanding the resource base (EIA 2016a).

As discussed in fact 2, prior CO₂ emissions have already resulted in substantial global temperature increases. If world economies

used all of the remaining fossil fuel resources that can be profitably extracted with current technology and prices, the total temperature impact is projected to be 2.8°F (1.6°C). Of course, technological progress could make this an underestimate of the potential warming to be expected from available fossil fuels. Were technological progress or price increases to induce the extraction of all additional currently known fossil fuel resources, further warming of 11.7°F (6.5°C) could be expected: 3.1°F from oil and gas and 8.6°F from coal (Greenstone 2015). Policy actions—and not the natural exhaustion of fossil fuel resources—will likely be required to avoid these outcomes.

FIGURE 3.
Estimated Temperature Impact of Combustion

Remaining fossil fuel resources are very extensive; unrestricted use would have huge effects on the climate.



Source: Greenstone 2015; Greenstone and Stuart 2015; Matthews et al. 2009.
Note: See Greenstone and Stuart (2015) for methodology. Fossil fuel reserves refer to those that can be profitably extracted with current technology and prices. “Oil and gas resources” and “Coal resources” refer to fossil fuel reserves that could be extracted with additional technological progress.

4. China and India’s share of cumulative global GHG emissions is projected to grow substantially by 2100.

The most important greenhouse gas—carbon dioxide—persists in the atmosphere for a very long and somewhat unpredictable length of time (IPCC 2007b). This is in contrast to other GHGs like methane that are removed relatively quickly from the atmosphere. Consequently, it is useful to focus not just on annual GHG emissions, but also on cumulative GHG emissions over a long period of time, which are more relevant for predicting temperature increase and climate change.

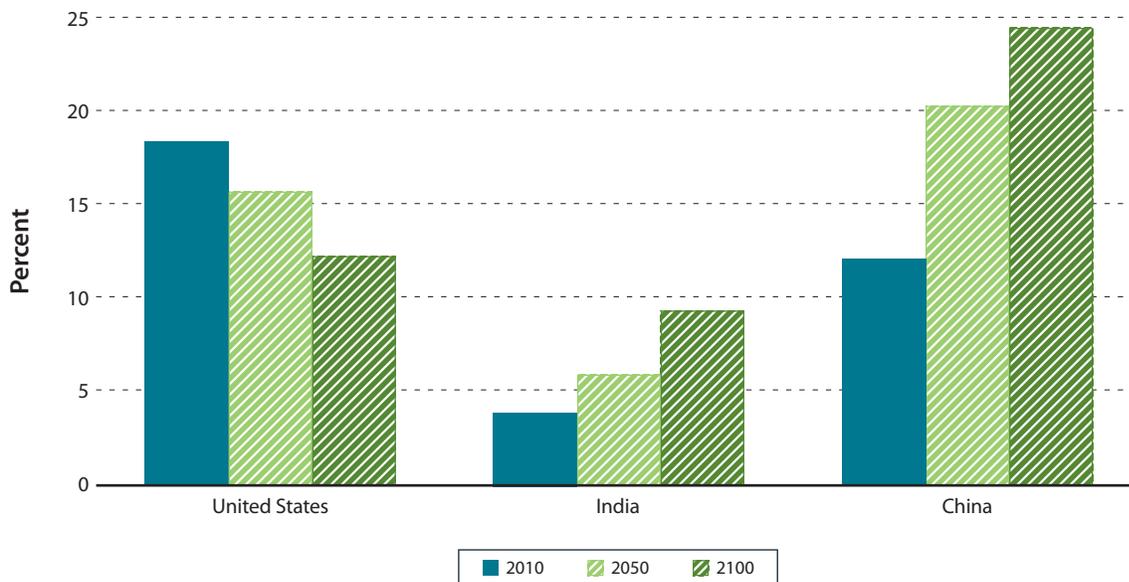
Because the United States industrialized many decades ago, it has produced sustained high levels of GHG emissions, accounting for a large share of global cumulative GHG emissions. By 2010

the United States had produced 18 percent of total global GHG emissions generated since 1850, as compared to only 4 percent generated by India and 12 percent by China. The U.S. share is projected to drop over time as developing countries’ GHG emissions grow and the United States continues to limit its new GHG emissions and experience relatively slow economic growth. By 2050 the shares of cumulative GHG emissions accounted for by China and India will be larger, at 20 and 6 percent, respectively, while the U.S. share will have dropped to 16 percent. By 2100 China and India will have produced over one-third of global cumulative GHG emissions.

FIGURE 4.

Share of Cumulative Global GHG Emissions, 2010–2100 (Projected)

By 2100 China and India’s shares of cumulative global GHG emissions are expected to be 2.0 and 2.5 times as high as 2010 levels, respectively, while the United States’ share of cumulative global GHG emissions is expected to fall to two-thirds of its 2010 level.



Source: EPIC calculations; Climate Interactive n.d.

Note: Cumulative emissions calculated starting in 1850. Striped bars for 2050 and 2100 are projections.

5. Over the next 70 years, every U.S. state is projected to experience increasing temperatures.

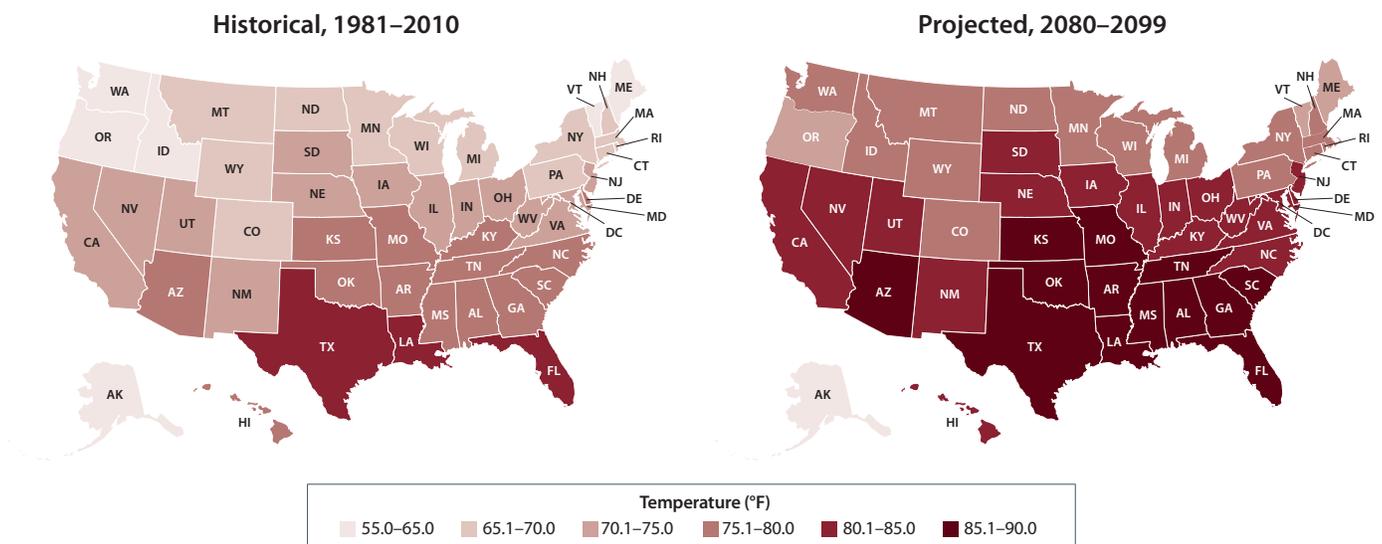
If global CO₂ emissions continue to grow according to their current trajectory, the United States will feature a very different range of climates than it currently does. By 2100 the majority of U.S. states would experience summers hotter than those of Mexico in 2012. Some states would experience even higher temperatures; for instance, Texas and 9 other states would have summers comparable to summer in Sudan in 2012 (World Bank n.d.).

As shown in the maps above, the entire Deep South—the exception of North Carolina—is projected to have an average summer temperature above 85°F (29.4°C) at the end of the current century. California, North Carolina, and Illinois would all be above 80°F (26.7°C).

Without adequate preparation, the implications for U.S. cities, industry, and agriculture would be alarming. High temperatures would cause hardship, as would drought and flooding. As discussed in a joint Hamilton Project and EPIC policy proposal by Matthew Kahn, climate change will necessitate costly adaptation by Americans and our local, state, and federal governments, most visibly through large-scale migration to areas that are less affected by climate change. In addition, many localities will need to make investments that protect them from the effects of climate change.

FIGURE 5. Average Summer Temperature by U.S. State, Historical and Projected, Based on Current CO₂ Emissions Trajectory

The number of states with average summer temperatures greater than 80°F (26.7°C) will increase from 3 to 31 by 2080–99.



Source: Climate Prospectus n.d.
 Note: “Current CO₂ emissions trajectory” refers to the representative concentration pathway 8.5, representing a continuation of recent global emissions growth rates and atmospheric concentrations of CO₂. The average of the months of June, July, and August is taken to calculate average summer temperature.



6. Much of U.S. infrastructure is vulnerable to the effects of climate change.

Much of U.S. infrastructure was not designed or built with climate change resiliency in mind. Partly for this reason, the projected costs of adapting to climate change are often large. For example, 190,000 bridges are considered to be vulnerable to flooding caused by projected climate change, and the cost of adaptation is estimated to be \$170 billion for 2010–2050 and \$24 billion for 2051–2100 (EPA 2015c). The estimated costs are front-loaded as a result of the large number of bridges that face near-term dangers from increased river flow. If investments are not made in adaptation, the economic damage from non-

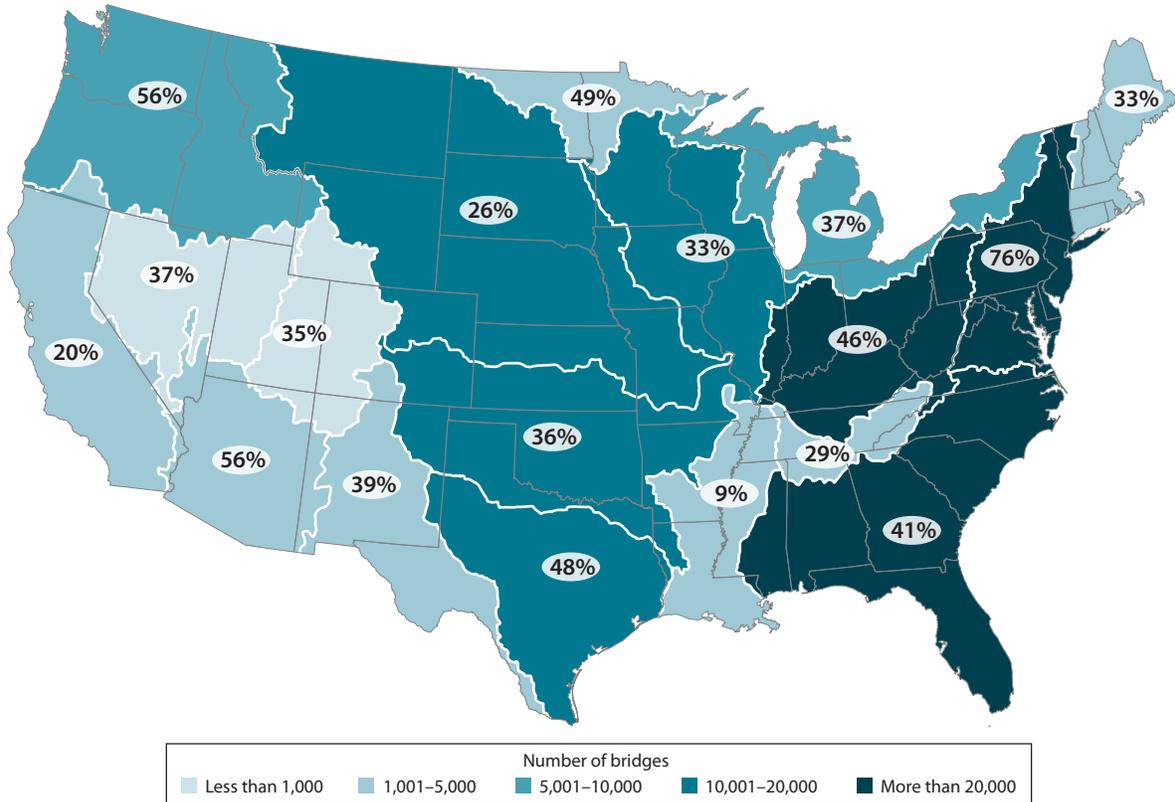
functional bridges would likely be even larger. Of course, if greenhouse gas emissions were reduced over the course of the 21st century, adaptation costs would be somewhat smaller.

Areas of vulnerability are especially concentrated east of the Mississippi River, where both a high absolute number and a high fraction of inland bridges are threatened. The local geological conditions, varying construction costs, and design of particular bridges all factor into projected vulnerability (Wright et al. 2012).

FIGURE 6.

Bridges Identified as Vulnerable Due to Projected Climate Change, 2051–2100

Many vulnerable bridges are located in the eastern United States.



Source: EPA 2015c.

Notes: Estimated number of vulnerable bridges in each of the 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. in the period from 2051–2100 under the Reference scenario using the IGSM-CAM climate model. The map also shows the percentage of inland bridges in each HUC that are vulnerable due to climate change.



7. The prices we pay for fossil fuels do not reflect their social costs.

The prices consumers pay for fossil fuels are low relative to costs for other energy sources. In particular, natural gas has become a very inexpensive source of energy. However, this is only one part—the private cost—of the total social cost of generating electricity with fossil fuels. These private costs are shown in blue in figure 7.

Because CO₂ emissions drive climate change that imposes costs on the broader society, the total social cost is considerably larger than the private cost. Of course, the social cost depends on assumptions made about damage from climate change. Using a U.S. government estimate of the cost of CO₂ pollution (\$40 per metric ton), the total social cost of a given energy source is shown as the sum of the blue and green bars.

After adding the cost of CO₂ pollution under this standard assumption, advanced natural gas and hydroelectric tie as the least expensive energy sources, though nuclear energy is only

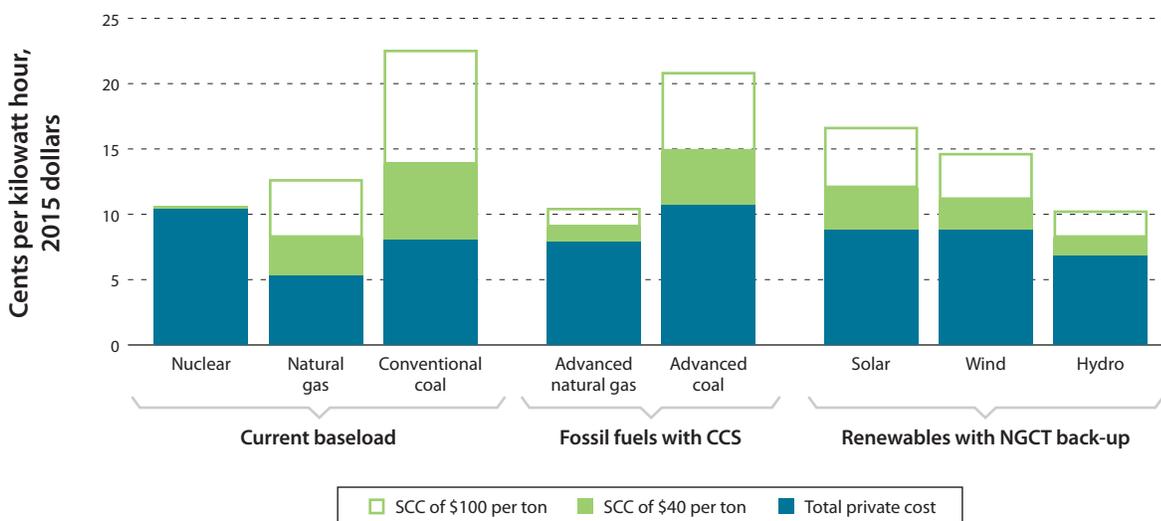
slightly more expensive. Note that, in this analysis, solar and wind energy are associated with CO₂ emissions because of the necessity of having a fossil fuel-powered backup during times of low light or wind.

Alternatively, if the cost of CO₂ pollution is assumed to be substantially higher—\$100 per metric ton—the total social cost is the sum of the blue, solid green, and hollow green bars. Hydroelectric energy then becomes the least costly energy source, while conventional coal production becomes the most expensive.

The technologies, policies, and other conditions that determine these prices are not fixed, of course. Market prices for renewable energy have dropped rapidly in recent years, and further technological progress is expected to lower the cost of solar energy in particular (International Renewable Energy Agency 2015).

FIGURE 7. Private and Social Cost of Energy for New Plants in 2023 (Projected)

At a carbon price of \$100 per ton, hydroelectric power is the least expensive source of electricity.



Sources: EPIC analysis based on data from Du and Parsons 2009; EIA 2013, 2014a, 2014b, 2015; EPA 2015a, 2015b, 2016a; FRED Economic Data 2016; Greenstone and Looney 2012; IRS 2016; Marten, Kopits, Griffiths, Newbold, and Wolverton 2014; NREL 2014; National Academy of Sciences 2010.
 Note: CCS = carbon capture and storage; NGCT = natural gas combustion turbine; SCC = social cost of carbon. The levelized cost of electricity is the present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments. Costs are levelized in real dollars. Since the costs of renewables reflect the inclusion of a combined cycle natural gas turbine to balance intermittency, the use of the NGCT with renewables produces CO₂ emissions and, therefore, social costs.

8. Electricity generation from renewable sources is expected to surpass generation from coal before 2050.

The electricity sector is experiencing revolutionary change. After decades of coal dominance in the United States, two important trends are evident, both of which act to reduce CO₂ emissions. First, natural gas has begun to supplant coal as the leading source of U.S. power generation. This development can in large part be ascribed to the discovery of U.S. natural gas resources that can now be recovered through the process of hydraulic fracturing (EIA 2016e).

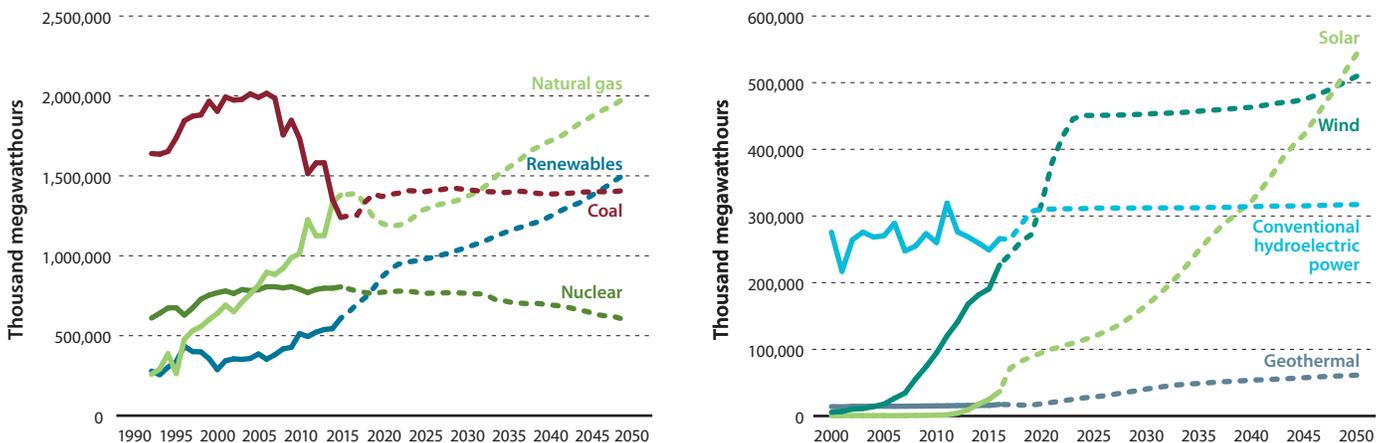
More recently, starting in the 2000s and accelerating in the 2010s, renewable electricity production has also substituted for coal-powered generation. Renewable power—derived largely from wind, solar, hydroelectric, and geothermal sources—is projected to exceed coal-powered generation by 2048. (These projections assume that the Clean Power Plan is not implemented.) Currently, wind and hydroelectric power are dominant within

the class of renewables, but solar power is projected to account for a larger share as its price falls (Wood 2016).

Both federal- and state-level policies have directly supported expansion of solar technology through a variety of tax credits (EIA 2016f). Large-scale solar power capacity has exploded in the past several years due to technological progress and support from government programs (DOE 2016). Capital costs—which have been a major barrier to expanded solar production in the past—dropped by half between 2010 and 2015 (EIA 2016f; IEA 2014). Steep learning curves, scale efficiencies, and increased competition have decreased installation costs for photovoltaic technology (National Renewable Energy Laboratory [NREL] 2016). However, factors such as slow electricity demand growth, low natural gas prices, and electricity grid and storage limitations may limit future growth potential for renewables (EIA 2016f).

FIGURE 8. U.S. Net Electricity Generation by Fuel Source, 2000–2050 (Projected)

Production of electricity from natural gas and renewables has increased in recent years, whereas production from coal has fallen.



Sources: EIA 1994, 1998, 2010, 2016a, 2016c, 2016d, 2017a, 2017b.
 Note: Data is for all sectors. Projections assume that the CPP is not implemented. Net electricity generation is the amount of gross electricity generation produced minus the electricity used to operate the power plant.

9. CO₂ emissions from transportation now exceed electric power emissions.

For decades, growth in emissions from the electric power sector outpaced that of the transportation sector. However, transportation recently surpassed the power sector as the largest source of U.S. energy-related CO₂ emissions in 2016 for the first time since 1979 (Vine 2016). Moreover, in its most recent long-term projections, the Department of Energy expects this dynamic to remain in place through 2040, even in the case where all current policies are extended (EIA 2016a).

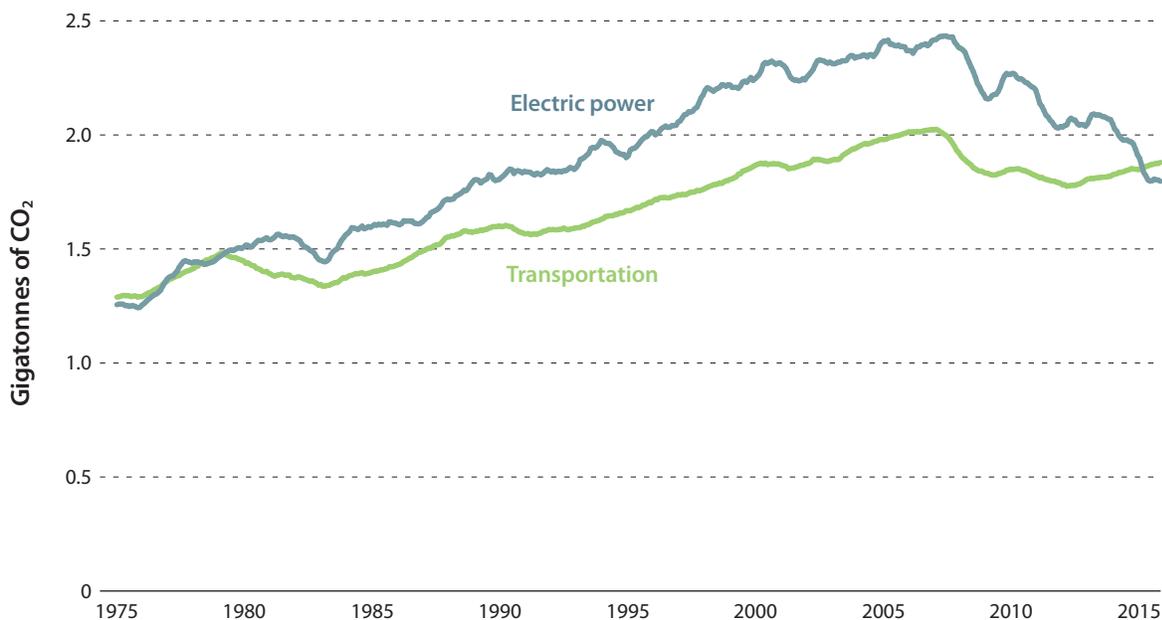
The shift in emissions sources is driven by two key factors. First, as can be seen in figure 9, power sector emissions have plunged since 2008, owing to a combination of the 2007–09 financial crisis, the rapid displacement of coal by cheaper

natural gas, and increasing renewable electricity generation. Second, transportation emissions have been on the rise since 2013, driven largely by the massive increase in U.S. highway vehicle miles traveled. Highway travel growth in 2015 and 2016 reached the highest levels since 1988, as was evident in fuel markets. Despite five years of progressively increasing fuel efficiency standards, U.S. gasoline demand set a historical record of 9.3 million barrels per day in 2016 (EIA 2016h).

In a joint Hamilton Project and EPIC policy proposal by Michael Greenstone, Cass Sunstein, and Sam Ori, the authors propose reforms that would more cheaply and effectively reduce CO₂ emissions in the transportation sector.

FIGURE 9.
U.S. CO₂ Emissions by Sector, 1975–2016

CO₂ emissions from transportation began to increase again in 2013.



Source: EIA 2016g.



10. Emissions from electric vehicles powered by coal plants are substantially higher than those powered by natural gas plants.

Vehicles powered in part or in full by electricity have become much more common in recent years (DOE 2016). The reduction in gasoline usage implied by the rise of electric vehicles is typically assumed to contribute to CO₂ emissions mitigation. Generally speaking, this is the case, but the details depend heavily on the fuel used to generate the electricity that powers the electric vehicle.

When powered by coal-fired plants, electric vehicles offer negligible CO₂ emissions mitigation benefits over the average new vehicle. However, when powered by the average U.S. natural gas plant, an electric vehicle contributes nearly 60

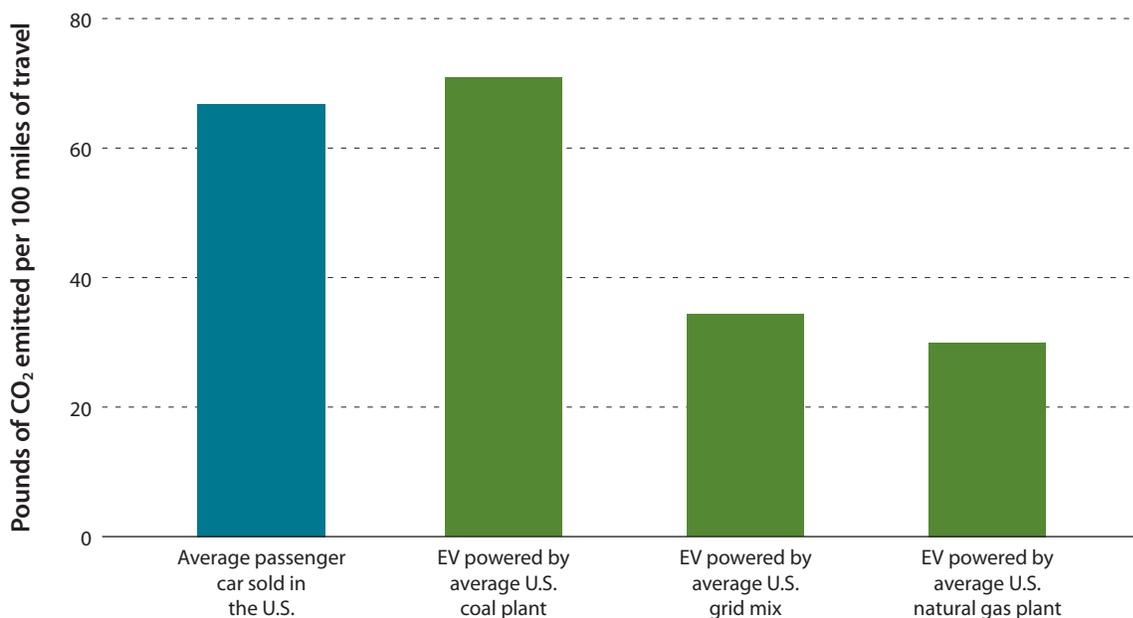
percent less CO₂ per mile than the average new gasoline-powered vehicle. When an electric vehicle is powered by the currently prevailing mix of energy sources in the United States, the gains are nearly as large.

This figure highlights the growing interaction between transportation and energy sector CO₂ emissions. As the range of energy sources for vehicles widens and electric vehicles become more common, it will become increasingly important to design policies that account for CO₂ emissions wherever they are generated.

FIGURE 10.

U.S. Electric Vehicle CO₂ Emissions

Electric vehicles hold the promise of substantially reduced CO₂ emissions, but improvements will depend on the electricity source.



Sources: EPIC calculations; EIA 2016b, 2016i, 2016j, 2016k; EPA 2016b, 2016c.
 Note: EV refers to electric vehicles. EV efficiency is 2015 Nissan Leaf equivalent. Calculations are only for fully electric vehicles and assume a 6 percent line loss. Emissions from mining or materials fabrication are not included. Estimates are for 2015.

11. Public investment in energy R&D remains well below 1970s and 1980s levels.

Government investment in energy-related research and development has varied considerably over time, alternately receiving encouragement during periods of perceived crisis and lower support during periods of low prices and abundant supply. The oil shocks of the 1970s were associated with high and rising spending on energy R&D, while relatively low conventional energy prices from the mid-1980s through mid-2000s were associated with reduced investment (Avato and Coony 2008). Notably, this pattern holds true across the industrialized nations shown in figure 11, reflecting the fact that they all experienced the same changes in global energy markets.

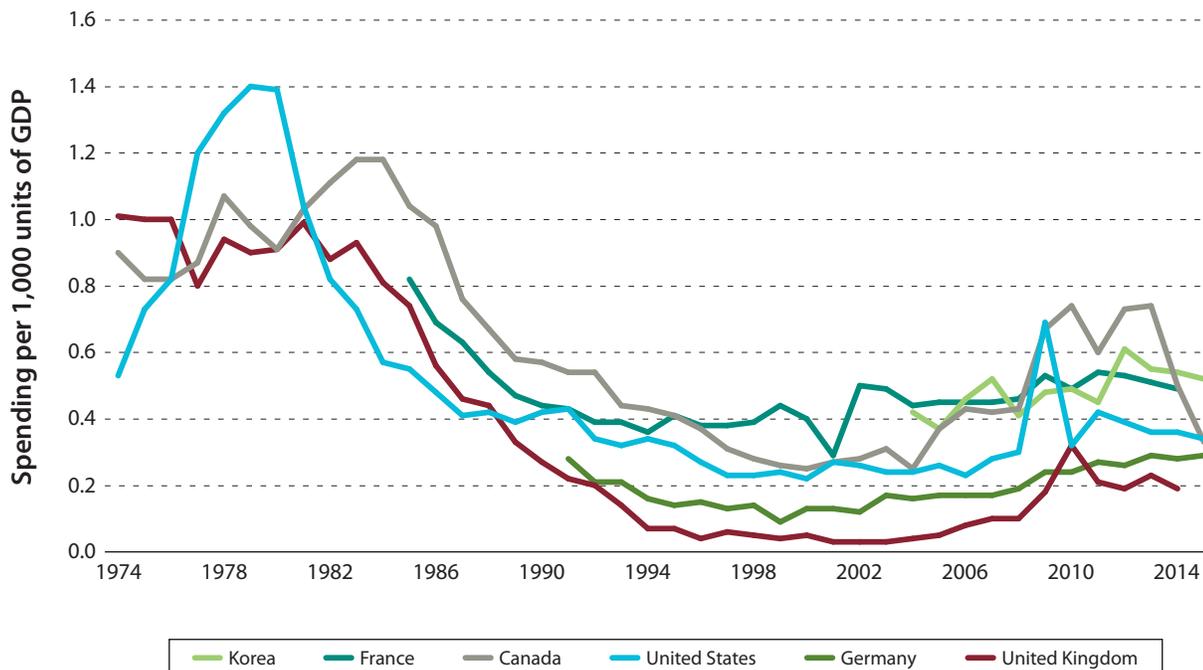
In the United States, the composition of public energy-related research and development investments has changed dramatically over the decades. In 1974, about three quarters of

U.S. public spending was devoted to nuclear technologies. In 2014, the nuclear energy share had shrunk to 14 percent, while spending on renewable and energy efficiency technologies had grown to 35 percent. A similar trend can be observed for other countries: for example, the United Kingdom’s investment in renewable and energy efficiency technology rose from 3 percent of its 1974 spending to 38 percent of its 2014 spending.

Technologies such as energy storage, advanced nuclear power, and carbon capture and sequestration hold considerable promise for providing scalable, clean energy. However, the costs for all of these technologies require further reductions in order to be economically competitive. Increased R&D investment may help to achieve this goal.

FIGURE 11. Public Spending on Energy-Related Research and Development, 1974–2015

Public energy investments have followed a similar pattern across countries.



Source: IEA n.d.

12. Investments in climate adaptation would greatly lower the burden of climate change.

Sea-level rise poses a physical and economic threat to much of the coastal United States. By one projection, sea-level rise of 0.9 meters by 2100—which is within the range of scenarios considered by climate scientists—would put 4.2 million Americans at risk of inundation. At the high end of sea-level rise scenarios, a 1.8 meter increase would put 13.1 million at risk of inundation (Hauer, Evans, and Mishra 2016).

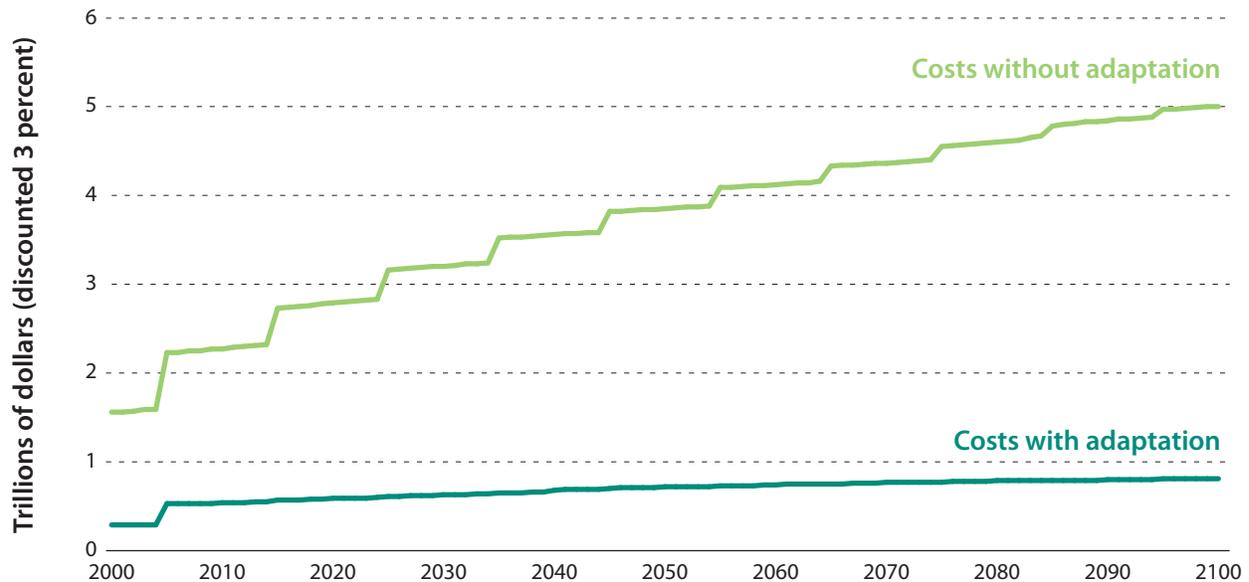
Sea-level rise, in conjunction with storm surges, will be very costly even if appropriate preparations are made. As shown in figure 12, the Environmental Protection Agency (2015c)

estimates that the cumulative expense of sea-level rise and storm surges associated with climate change would be roughly \$810 billion by 2100. If no preparations are made, the costs are far higher, at a cumulative \$5 trillion by 2100.

These costs will take a number of forms: abandonment of property and damage from storms both figure prominently. Adaptation will itself be costly, even though it prevents larger costs from being incurred. Elevating properties above sea level and reinforcement of shorelines, for example, will generate costs in the scenario with adaptation.

FIGURE 12.
Cost of Sea-level Rise and Storm Surge to Coastal Property, by Response

Adaptation investments would prevent trillions of dollars of cumulative costs related to sea-level rise and storm surge.



Source: EPA 2015c.

Notes: The step-wise nature of the graph is due to the fact that storm surge risks are evaluated every ten years, beginning in 2005. Costs with adaptation include the value of abandoned property, residual storm damages, and costs of protective adaptation measures.



Technical Appendix

Fact 1. The United States possesses ample affordable energy.

Data come from the EIA February 2017 Monthly Energy Review, with data for November 2016, tables 1.2 and 1.3. Yearly consumption is the sum of the categories “Gasoline and other energy goods” and “Electricity and gas” services in Table 2.4.5, Personal Consumption Expenditures by Type of Product from the Bureau of Economic Analysis NIPA tables. Other renewables refers to the sum of geothermal, solar, wind, and biomass energy production.

Fact 4. China and India’s share of cumulative global GHG emissions is projected to grow substantially by 2100.

These results come from the RCP6.0 scenario from the Climate Interactive C-ROADS Pro model. Cumulative GHG emissions are measured with a baseline year of 1850.

Fact 7. The prices we pay for fossil fuels do not reflect their social costs.

The levelized cost of electricity is calculated using the standard approach outlined by EIA (2013). The total levelized cost of electricity without government penalties or benefits is calculated using the methodology of Greenstone and Looney (2012) and projections of components private costs from the EIA NEMS model. Where possible EIA derives cost estimates from actual or planned projects, and otherwise uses costing models that account for current labor, material, and contractual agreements (e.g., for CCS plants). A theoretical natural gas backup is added in for renewable technologies in order to show comparisons with baseload technologies of similar capacity factors. Social costs are added on top of private costs, using data from NREL, NAS, and EPA estimates.

Fact 8. Electricity generation from renewable sources is expected to surpass generation from coal before 2050.

For data in years 1993–2015, the category for renewables sums conventional hydroelectric power and other renewables. Solar is the sum of “Solar Thermal” and “Solar Photovoltaic” and Wind is the sum of “Wind” and “Offshore Wind” from “Renewable Energy Generation by Fuel” on the EIA Annual Energy Outlook.

Fact 9. CO₂ emissions from transportation now exceed electric power emissions.

Data come from EIA 2016g tables 12.5 and 12.6. Monthly levels were calculated by taking the sum over the previous 12 months.

Fact 10. Emissions from electric vehicles powered by coal plants are substantially higher than those powered by natural gas plants.

Electric power generation data come from EIA 2016i, table 7.2b. Electric power CO₂ emissions data come from EIA 2016i table 12.6. A line loss of 6% is assumed, as estimated in EIA 2016j. New car fuel efficiency data come from EPA 2016b, table 3.2. Pounds of CO₂ (19.64) produced from burning a gallon of gasoline is taken from EIA 2016j. Electric power generation is divided by electric power CO₂ emissions to calculate metric tons of CO₂ per kWh. This number is multiplied by 2205 to calculate pounds of CO₂ per kWh, then divided by 94 percent (100 percent minus the line loss), and multiplied by 100 times the EV efficiency of 0.30 to calculate pounds of CO₂ emissions per 100 miles of travel.

References

- Ackerman, Frank and Elizabeth A. Stanton. 2008. "What We'll Pay if Global Warming Continues Unchecked." *Natural Resources Defense Council*.
- Avato, Patrick, and Jonathan Coony. 2008. "Accelerating Clean Energy Technology Research, Development, and Deployment: Lessons from Non-Energy Sectors." Working Paper 138, World Bank Publications, The World Bank, Washington, DC.
- BGR (Bundesanstalt für Geowissenschaften und Rohstoffe). 2015, December. "2015 Energy Study: Reserves, Resources, and Availability of Energy Resources." BGR, Hannover, Germany.
- Bureau of Economic Analysis (BEA). n.d. "National Income and Product Accounts Tables." Bureau of Economic Analysis, U.S. Department of Commerce, Washington, DC.
- Climate Interactive. n.d. "Climate Scoreboard." Climate Interactive, Washington, DC.
- Climate Prospectus. n.d. "ACP Physical Climate Data Tables." Climate Prospectus.
- Department of Energy (DOE). 2016. "Fact #918: March 28, 2016 Global Plug-In Light Vehicle Sales Increased by About 80% in 2015." Transportation Fact of the Week Newsletter, Vehicle Technologies Office, U.S. Department of Energy, Washington, DC.
- Du, Yangbo, and John E. Parsons. 2009. "Update on the Costs of Nuclear Power." Working Paper 09-004, Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA.
- Energy Information Administration (EIA). 1994. "Electric Power Annual 1993." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 1998. "Electric Power Annual 1997 Volume I." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2010. "Electric Power Annual 2008." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2013. "Levelized Cost of Electricity and Levelized Avoided Cost of Electricity Methodology Supplement." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2014a. "Table F23: Nuclear Energy Consumption, Price, and Expenditure Estimates, 2014." State Energy Data System, Energy Information Administration, U.S. Department of Energy, Washington, DC. http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_nu.pdf.
- . 2014b. "The Electricity Market Module of the National Energy Modeling System: Model Documentation 2014." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2015. "U.S. Natural Gas Gross Withdrawals," Energy Information Administration, U.S. Department of Energy, Washington, DC. <https://www.eia.gov/dnav/ng/hist/n9010us2A.htm>.
- . 2016a. "Annual Energy Outlook 2016." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016b. "How Much Carbon Dioxide is Produced by Burning Gasoline and Diesel Fuel?" Independent Statistics & Analysis: Frequently Asked Questions, Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016c. "Electric Power Annual 2014." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016d. "Electric Power Monthly July 2016." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016e. "Hydraulically Fractured Wells Provide Two-thirds of U.S. Natural Gas Production." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016f. "Wind and Solar Data and Projections from the U.S. Energy Information Administration: Past Performance and Ongoing Enhancements." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016g. "Monthly Energy Review, September 2016." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016h. "Table 4: U.S. Petroleum and Other Liquids Supply, Consumption, and Inventories." Short-Term Energy Outlook, Independent Statistics & Analysis, Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016i. "Monthly Energy Review, October 2016." Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2016j. "How Much Electricity Is Lost in Transmission and Distribution in the United States?" Independent Statistics & Analysis: Frequently Asked Questions, Energy Information Administration, U.S. Department of Energy, Washington, DC.

- . 2016k. “Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016.” Independent Statistics & Analysis, Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2017a. “Annual Energy Outlook 2017.” Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2017b. “Electric Power Monthly November 2016.” Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . 2017c. “Monthly Energy Review November 2016.” Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . n.d.a. “Liquefied U.S. Natural Gas Exports.” Energy Information Administration, U.S. Department of Energy, Washington, DC.
- . n.d.b. “U.S. Exports of Crude Oil.” Energy Information Administration, U.S. Department of Energy, Washington, DC.
- Environmental Protection Agency (EPA). 2015a. “Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2013” Environmental Protection Agency, Washington, DC.
- . 2015b. “The Social Cost of Carbon.” Environmental Protection Agency, Washington, DC. <https://www3.epa.gov/climatechange/EPAactivities/economics/scc.html>.
- . 2015c. “Climate Change in the United States: Benefits of Global Action.” Office of Atmospheric Programs, Environmental Protection Agency, Washington, DC.
- . 2016a. “Coal Mine Methane Units Converter.” Environmental Protection Agency, Washington, DC. <https://www.epa.gov/epa-coalbed-methane-outreach-program/units-converter>.
- . 2016b. “Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2014.” Environmental Protection Agency, Washington, DC.
- . 2016c. “Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016.” Environmental Protection Agency, Washington, DC.
- FRED Economic Data. 2016. “Gross Domestic Product: Implicit Price Deflator.” FRED Economic Data, Federal Reserve Bank of St. Louis, St. Louis, MO.
- Goddard Institute for Space Studies (GISS). n.d. “Global Land-Ocean Temperature Index.” Goddard Institute for Space Studies, National Aeronautics and Space Administration, Washington, DC. <http://climate.nasa.gov/vital-signs/global-temperature/>.
- Greenstone, Michael. 2015. “If We Dig Out All Our Fossil Fuels, Here’s How Hot We Can Expect It to Get,” *New York Times*, April 8.
- Greenstone, Michael, and Adam Looney. 2012. “Paying Too Much for Energy? The True Costs of Our Energy Choices.” *Daedalus* 141 (2): 10–30.
- Greenstone, Michael, and Daniel Stuart. 2015, December. “Calculating the Temperature Potential of Fossil Fuels.” Analysis, Energy Policy Institute at University of Chicago (EPIC), Chicago, IL. <https://epic.uchicago.edu/sites/default/files/Calculating%20the%20Temperature%20Potential%20of%20Fossil%20Fuels.pdf>.
- Hatfield, Jerry, Gene Takle, Richard Grotjahn, Patrick Holden, R. Cesar Izaurralde, Terry Mader, Elizabeth Marshall, and Diana Liverman. 2014. “Agriculture.” In *Climate Change Impacts in the United States: The Third National Assessment*, edited by J.M. Melillo, Terese Richmond, and G.W. Yohe, chapter 6. Subcommittee on Global Change Research, committee on Environment, Natural Resources, and Sustainability, National Science and Technology Council, Office of Science and Technology Policy, Executive Office of the President, Washington, DC.
- Hauer, Mathew E., Jason M. Evans, and Deepak R. Mishra. 2016. “Millions Projected to Be at Risk from Sea-Level Rise in the Continental United States.” *Nature Climate Change* 6 (7): 691–5.
- Intergovernmental Panel on Climate Change (IPCC). 2007a. *Climate Change 2007 Impacts, Adaptation and Vulnerability*, edited by M.L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C.E. Hanson. Working Group II to the Fourth Assessment Report, Intergovernmental Panel on Climate Change, Geneva, Switzerland. Cambridge, UK: Cambridge University Press.
- . 2007b. *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller. Working Group I to the Fourth Assessment Report, Intergovernmental Panel on Climate Change, Geneva, Switzerland. Cambridge, UK and New York, NY: Cambridge University Press.
- Internal Revenue Service (IRS). 2016, August. “How to Depreciate Properly.” Publication 946, Internal Revenue Service, U.S. Department of the Treasury, Washington, DC.

- International Energy Agency (IEA). 2014, September. "How Solar Energy Could Be the Largest Source of Electricity by Mid-Century." International Energy Agency, Paris.
- . n.d. "RD&D Statistics Database." International Energy Agency, Paris.
- International Renewable Energy Agency (IRENA). 2015, January. "Renewable Power Generation Costs in 2014." Abu Dhabi, United Arab Emirates.
- Jones, Andrew, John Sterman, and Ellie Johnston. 2016. "Paris Agreement Pledges Must Be Strengthened in Next Few Years to Limit Warming to 2 Degrees Celsius." Climate Scoreboard, Climate Interactive and Massachusetts Institute of Technology Sloan School of Management.
- Marten, Alex, Elizabeth A. Kopits, Charles Griffiths, Stephen Newbold, and Ann Wolverton. 2014. "Incremental CH₄ and N₂O Mitigation Benefits Consistent with the US Government's SC-CO₂ Estimates." *Climate Policy* 15 (2). doi: 10.1080/14693062.2014.912981.
- Matthews, H. Damon, Nathan P. Gillet, Peter A. Stott, and Kirsten Zickfeld. 2009. "The Proportionality of Global Warming to Cumulative Carbon Emissions." *Nature* 459: 829–32.
- National Academy of Sciences. 2010. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. Washington, DC: The National Academies Press.
- National Oceanic and Atmospheric Administration (NOAA). 2016. "NOAA ESRL Data." Global Monitoring Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Boulder, CO.
- National Renewable Energy Laboratory (NREL). 2014, July. "Life Cycle Assessment Harmonization Results and Findings." National Renewable Energy Laboratory, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. http://www.nrel.gov/analysis/sustain_lca_results.html.
- . 2016, February. "Distributed Generation Renewable Energy Estimate of Costs." National Renewable Energy Laboratory, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC.
- Tripati, Aradhna K., Christopher Roberts and Robert A. Eagle. 2009. "Coupling of CO₂ and Ice Sheet Stability Over Major Climate Transitions of the Last 20 Million Years." *Science* 326 (5958): 1394–7.
- Vine, Doug. 2016, June 20. "Transportation Emissions Roll Over Power Sector Emissions." Center for Climate and Energy Solutions, Arlington, VA.
- Wood, Daniel. 2016, September 28. "Six Charts that Will Make You Optimistic About America's Clean Energy Future." U. S. Department of Energy, Washington, DC.
- World Bank. n.d. *Historical Average Monthly Temperature*. Climate Change Knowledge Portal, World Bank, Washington, DC.
- Wright, Len et al. 2012, December. "Estimated effects of climate change on flood vulnerability of U.S. bridges." *Mitigation and Adaptation Strategies for Global Change* 17 (8): 939–55.

Select Hamilton Project and EPIC Papers on Energy and the Environment

ECONOMIC FACTS

- **“In Times of Drought: Nine Economic Facts about Water in the United States”**

Melissa Kearney, Benjamin Harris, Brad Hershbein, Elisa Jácome, and Greg Nantz

The water crisis is as much an economic issue as it is an environmental one, and it demands focused national attention. This Hamilton Project series of nine economic facts about water in the United States focuses on relevant background context to the water crisis as well as on supply and demand issues. It discusses three topics: the occurrence of drought in the United States, the importance of water to the U.S. economy, and barriers to efficient uses of water.

STRATEGY & FRAMING PAPERS

- **“Energy Policy Opportunities and Continuing Challenges in the Presence of Increased Supplies of Natural Gas and Petroleum”**

Michael Greenstone, Adam Looney, Dmitri Koustas, Karen Li, and Harrison Marks

This framing paper provides a summary of some of the recent changes in the energy sector, tallies the benefits and costs, and speculates about the changes yet to come. It discusses five principles for shaping sound energy and environmental policy, and addresses the vast increase in the supplies of natural gas and petroleum in the United States.

POLICY PROPOSALS

- **“The Next Generation of Transportation Policy”**

Michael Greenstone, Cass Sunstein, and Sam Ori

Michael Greenstone, Cass Sunstein, and Sam Ori propose reforms to fuel efficiency standards for U.S. vehicles. Current standards allow light trucks and larger vehicles to emit at higher levels, focus on efficiency without consideration of lifetime vehicle usage, do not guarantee emissions reductions, and do not establish an effective market for trading credits. Greenstone, Sunstein, and Ori’s proposal removes considerations of vehicle type and size, refocuses on lifetime vehicle emissions, and establishes a robust cap-and-trade program for vehicle emissions.

- **“Protecting Urban Places and Populations from Rising Climate Risk”**

Matthew E. Kahn

Matthew Kahn of the University of Southern California proposes to implement a series of policies to improve urban climate change adaptation strategies, including investing in infrastructure, assisting those who are most vulnerable to climate risks, and allowing markets to accurately reflect potential climate threats.

- **“Federal Minerals Leasing Reform and Climate Policy”**

Kenneth T. Gillingham and James H. Stock

Kenneth T. Gillingham of Yale University and James H. Stock of Harvard University propose reforms to the federal minerals leasing program that both tie it to negative climate effects associated with coal mining, and improve its efficiency and benefits to the taxpayer. Specifically, they propose applying a royalty adder of 20 percent of the social cost of carbon to new and renewed federal coal leases.

- **“The Many Benefits of a Carbon Tax”**

Adele Morris

Adele Morris proposes a carbon tax as a new source of revenue that could also help address climate change. She suggests that a carbon tax would reduce the buildup of greenhouse gasses, replace command-and-control regulations and expensive subsidies with transparent and powerful market-based incentives, and promote economic activity through reduced regulatory burden and lower marginal tax rates.

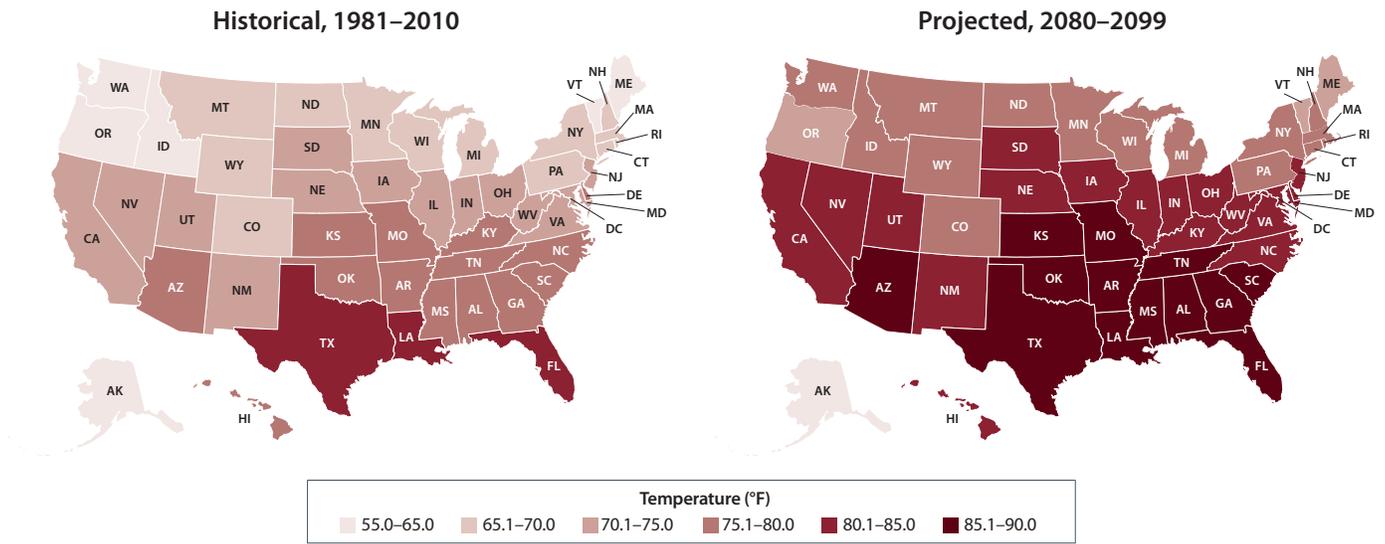
- **“Eliminating Fossil Fuel Subsidies”**

Joseph Aldy

Limiting subsidies for fossil fuels could raise revenue for the federal government while also benefiting the environment. Joseph Aldy proposes eliminating twelve subsidies to help level the playing field among fossil fuel producers relative to other businesses. This proposal aims to lower global fuel prices by providing the United States with increased leverage in negotiations over eliminating fossil fuel subsidies in the developing world.

Average Summer Temperature by U.S. State, Historical and Projected, Based on Current CO₂ Emissions Trajectory

The number of states with average summer temperatures greater than 80°F (26.7°C) will increase from 3 to 31 by 2080–99.



Source: Climate Prospectus n.d.

Note: "Current CO₂ emissions trajectory" refers to the representative concentration pathway 8.5, representing a continuation of recent global emissions growth rates and atmospheric concentrations of CO₂. The average of the months of June, July, and August is taken to calculate average summer temperature.



Facts on Energy and Climate Change:

1. The United States possesses ample affordable energy.
2. Global temperatures are rising.
3. Global temperatures would likely rise by another 14.5°F (8°C) if all remaining global fossil fuel resources were used.
4. China and India's share of cumulative global GHG emissions is projected to grow substantially by 2100.
5. Over the next 70 years, every U.S. state is projected to experience increasing temperatures.
6. Much of U.S. infrastructure is vulnerable to the effects of climate change.
7. The prices we pay for fossil fuels do not reflect their social costs.
8. Electricity generation from renewable sources is expected to surpass generation from coal before 2050.
9. CO₂ emissions from transportation now exceed electric power emissions.
10. Emissions from electric vehicles powered by coal plants are substantially higher than those powered by natural gas plants.
11. Public investment in energy R&D remains well below 1970s and 1980s levels.
12. Investments in climate adaptation would greatly lower the burden of climate change.

