Chapter 4

Energy: Innovation and Independence

U.S. energy innovation has continued to flourish under the Trump Administration. Innovation—and the policies that support it—lowers costs and prices, and increases production. This is illustrated by the American shale revolution and its dramatic rise in oil and gas drilling productivity in shale and similar geologic formations. Gains in shale drilling productivity have led to lower prices for natural gas, electricity, and oil, saving the average family of four $2,500 annually. Shale-driven savings represent a much larger percentage of income for the lowest fifth of households than for the highest fifth.

Production growth due to shale innovation has also brought energy independence to the United States, a goal first set by President Richard M. Nixon, and pursued by subsequent Administrations, but accomplished under the Trump Administration. In 2017, the United States became a net exporter of natural gas for the first time since 1958; and in September 2019, the United States became a net exporter of crude oil and petroleum products and is projected to remain a net exporter for all of 2020 for the first time since at least 1949. Historically, a rise in energy prices increased the trade deficit and costs for firms and households, sometimes pushing the U.S. economy into a recession. The innovation-driven surge in production and exports has made the U.S. economy more resilient to global oil price spikes. It has also improved the country's geopolitical flexibility and influence, as evidenced by concurrent sanctions on two major oil-producing countries, Iran and Venezuela.

In addition to consumer savings and energy independence benefits, the shale revolution has reduced carbon dioxide and particulate emissions through changes in the composition of electricity generation sources. We estimate that from 2005 to 2018, the shale revolution in particular lowered carbon dioxide emissions in the electric power sector by 21 percent. This contributed to a greater decline in carbon dioxide and particulate emissions (relative to the size of the economy) in the United States than in the European Union, according to the most recent data.

The Trump Administration's deregulatory energy policy follows earlier Federal deregulatory policies that helped to spur the shale revolution. By limiting unnecessary constraints on private innovation and investment, the Administration supports further unleashing of the country's abundant human and energy resources. In contrast, the State of New York has banned shale production and stymied new pipeline construction, leading to falling natural gas production in the State, greater reliance on energy produced elsewhere, and higher energy prices. Similarly, evidence on renewable energy mandates at the State and Federal levels shows their costs and limitations. More broadly, predicting the evolution of energy markets and technologies remains difficult—few anticipated the shale revolution's effect on lower prices for natural gas, electricity, and oil or the current economic challenges in the nuclear power sector. This difficulty highlights the value of policies that avoid picking winners and losers and instead provides a broad platform upon which innovation will flourish.

The classic effects of innovation are improvements in productivity, which lower costs and prices and increase production.[1] Energy sector innovations—and the policies that support them—have similar effects and ultimately reduce prices for American households and businesses. This chapter describes the causes and consequences of growth in oil and natural gas production from shale and similar geologic formations, while also highlighting broader energy sector innovations and policy questions. We first discuss the dramatic rise in productivity and its effects on cost, production, and price. Second, we estimate the consumer savings brought by shale-driven declines in energy prices. Third, we document how the surge in shale production has led to

[1] The CEA previously released research on topics covered in this chapter. The text that follows builds on the report "The Value of U.S. Energy Innovation and Policies Supporting the Shale Revolution" (CEA 2019).

U.S. energy independence, as measured by positive net exports of both oil and natural gas. Fourth, we assess total and shale-related changes in emissions in the United States. Finally, we consider the implications of deregulatory versus government-directed energy policies.

From 2007 to 2019, innovation in shale production brought an 8-fold increase in extraction productivity (new well production per rig) for natural gas and a 19-fold increase for oil. These productivity gains have reduced costs and spurred production to record-breaking levels. As a result, the United States has become the world's largest producer of both commodities, surpassing Russia in 2011 (for natural gas) and Saudi Arabia and Russia in 2018 (for oil). The Council of Economic Advisers (CEA) estimates that greater productivity reduced the domestic price of natural gas by 63 percent as of 2018 and led to a 45 percent decrease in the wholesale price of electricity. The increase in U.S. oil production linked to shale oil development helped not only moderate but also reduce the global price of oil over the same period in the face of "peak oil" forecasts. By lowering energy prices, we estimate that the shale revolution saves U.S. consumers $203 billion annually, or $2,500 for a family of four. Nearly 80 percent of the total savings stem from a substantially lower price for natural gas, of which more than half comes from lower electricity prices. Because low-income households spend a larger share of their income on energy bills, lower energy prices disproportionately benefit them; shale-driven savings represent 6.8 percent of income for the lowest fifth of households, compared with 1.3 percent for the highest fifth. These consumer savings are in addition to economic benefits linked to greater employment in the sector.

At the same time, shale-driven production growth has fulfilled the nearly 50-year goal of U.S. energy independence. In 2017, the United States became a net exporter of natural gas for the first time since 1958; and in September 2019, the United States became a net exporter of crude oil and petroleum products and is projected to remain a net exporter for all of 2020 for the first time since at least 1949. The long-standing goal of energy independence was motivated by the historic vulnerability of the U.S. economy to oil price spikes. Historically, a rise in energy prices increased the trade deficit and costs for firms and households, potentially pushing the U.S. economy into a recession. In fact, a sudden rise in the price of oil preceded 10 of the 11 postwar recessions in the United States (Hamilton 2011). With energy independence, spikes in global energy prices continue to affect U.S. households and businesses, but they now have a more muted effect on gross domestic product (GDP) because they do not inflate the trade deficit as they did when net imports were high. From 2000 to 2010, a $1 increase in oil prices reduced the U.S. trade balance in goods by $0.83 billion; from 2011 to 2019, it reduced it by only $0.17 billion. Higher prices could even increase GDP if they cause a large enough increase in investment by U.S. energy producers. Greater exports and resilience to price shocks have also improved the country's geopolitical flexibility and influence, as evidenced by concurrent sanctions on two major oil producers.

In addition to consumer savings and energy independence benefits, the shale revolution has reduced carbon dioxide and particulate emissions through changes in the composition of electricity generation sources. The CEA estimates that from 2005 to 2018, the shale revolution in particular was responsible for reducing electric power sector carbon dioxide emissions by 21 percent. This contributed to a greater decline in carbon dioxide emissions and particulate emissions (relative to the size of the economy) in the United States than in the European Union from 2005 to 2017, the most recent year for data in both areas.

The Trump Administration's deregulatory energy policy follows earlier Federal deregulatory policies that helped to spur the shale revolution. By limiting unnecessary constraints on private innovation and investment, the Administration's deregulatory policy supports further unleashing of the country's abundant human and energy resources. In contrast, the State of New York has banned shale production and stymied new pipeline construction, leading to falling natural gas production in the State, greater reliance on energy produced elsewhere, and higher energy prices. Similarly, evidence on renewable energy mandates at the State and Federal levels shows their costs and limitations. More broadly, predicting the evolution of energy markets and technologies remains difficult—few anticipated the shale revolution's effect on lower prices for natural gas, electricity, and oil or the current economic challenges in the nuclear power sector. This highlights the value of policies that avoid picking winners and losers and instead provides a broad platform upon which innovation will flourish.

Market Pricing, Resource Access, and Freedom to Innovate

Growth in the extraction of oil and natural gas from shale and similar geologic formations—often referred to as the shale revolution—is arguably the most consequential energy development in the last half century. Its far-reaching consequences are in part because fossil fuels account for 80 percent of U.S. energy consumption (EIA 2019b). Most oil goes to fuel the planes, trains, and automobiles of the transportation sector, while most natural gas generates electric power or heat for industry and households.

Since at least the late 1970s, geologists knew that shale and other low-permeability formations contained prodigious amounts of natural gas. For decades, methods to profitably extract the gas eluded the industry, much of which pursued easier-to-access resources in the United States and abroad. Although various countries have abundant shale resources, entrepreneurs and engineers working in the United States' innovation-friendly context first unlocked the potential of shale, which would eventually bring large savings to consumers and environmental benefits relative to a scenario without shale development.

The shale revolution came after major deregulatory changes in the governance of natural gas pricing and distribution. Three major deregulatory actions—the 1978 Natural Gas Policy Act, the Federal Energy Regulatory Commission's 1985 Open Access Order, and the 1989 Natural Gas Wellhead Decontrol Act—liberalized access to pipelines and increased the role of market forces in determining prices paid to natural gas producers. Earlier price controls discouraged production and exploration, leading to supply shortages. Once freed to move with supply and demand, wellhead prices increased, encouraging more innovation, which eventually lowered prices (MacAvoy 2008). Prices, however, would begin to increase again in the late 1990s and early 2000s.

Higher wellhead prices justified taking innovative risks on new methods and geologic formations, and private ownership of underground resources made it easy for firms to access these resources and experiment in diverse locations. The United States is unique in that the private sector—homeowners, farmers, and businesses—owns the majority of subsurface mineral rights. This system allows private owners to grant access to energy firms through lease contracts, which can be for one-tenth of an acre or 10,000 acres (Fitzgerald 2014). As a result, energy firms do not need to navigate a cumbersome central government bureaucracy to begin accessing subsurface resources. Although firms must still abide by Federal and State regulations, gaining the right to access resources is straightforward—they just need to adequately compensate the owner of the relevant acreage.

The role of the Federal government in unlocking the shale revolution is often overstated. Certainly, the U.S. Department of Energy's (DOE) investment of about $130 million from 1978 to 1992 in Federal funding for research on drill bit technology, directional drilling, modeling for shale basin reservoirs, and microseismic monitoring of multistage hydraulic fracturing treatment helped spur sector innovation. A more detailed analysis shows that primary credit belongs to the private sector. Federally subsidized research to aid the development of shale gas in the East carried limited transferability to the early breakthroughs in Barnett shale formation. Moreover, an early tax credit aimed at stimulating the production of natural gas from unconventional sources expired in 1992, well before important breakthroughs in the early 2000s.[2]

Among firms pioneering in shale extraction, the most important is arguably Mitchell Energy. In the 1980s and 1990s, Mitchell Energy, which had long-term contracts to sell its natural gas, experimented with methods to coax natural gas from a Texas geologic formation known as the Barnett Shale.

[2] Wang and Krupnick (2015) discuss Federal government policies that may have aided Mitchell Energy as it experimented in the Barnett and generally conclude that subsidies, tax credits, tax-preferred business structure, and research and development played a secondary role.

Consistent commercial success emerged in the early 2000s, when Devon Energy acquired Mitchell Energy. This acquisition accelerated the merger of two complementary technologies. Devon had considerable experience with horizontal drilling, which involves drilling a conventional vertical well, and at the bottom of the vertical leg, transitioning to a horizontal leg, which can extend for several miles. Mitchell Energy had more experience pumping liquids and sand under high pressure into wells to fracture low-permeability formations, thereby releasing gas and/or oil trapped in the rock. This stimulation technique is known as hydraulic fracturing (Wang and Krupnick 2015). Promising results from Devon's wells, coupled with rising natural gas prices, spurred a drilling boom in the Barnett Shale. Thus, the number of well permits issued in the Barnett grew from less than 300 in 2000 to more than 4,000 in 2008. The revolution had begun.

The shale revolution may not have been sustained if it had not been for continued innovation by scores of engineers, geologists, and entrepreneurs, who refined and adapted methods to draw oil from western North Dakota and southern Texas as well as natural gas from Appalachia in the Eastern United States. Persistent innovation and opportunity for its diffusion has transformed energy markets, with considerable implications for consumers and the environment.

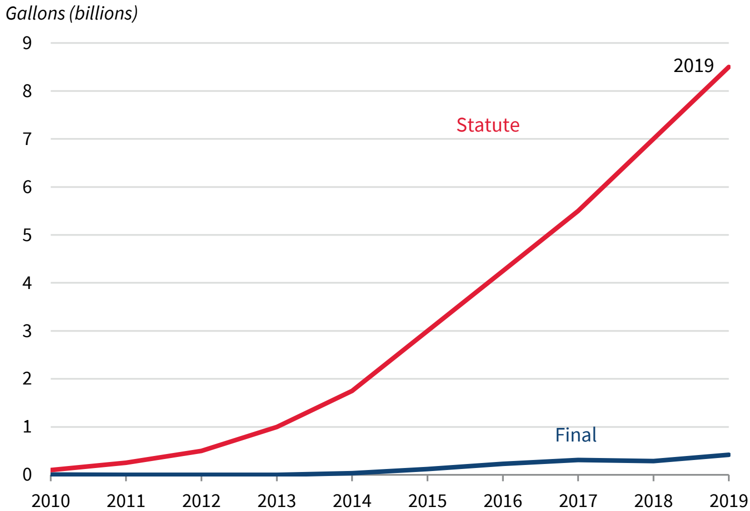
Important innovations have also occurred elsewhere in the energy sector. Advances in the design of combined-cycle turbines in natural gas plants have allowed the plants to generate more electricity from each unit of heat. From 2008 to 2017, the amount of heat needed to generate a kilowatt-hour of electricity declined by 10 percent. In addition, the cost of turbines, measured in dollars per unit of capacity, has fallen by 11 percent since 2014. Alongside more efficient and less costly natural gas turbines, the cost of wind power projects has also fallen recently, causing wind power prices to fall by more than 50 percent from 2010 to 2017. These gains stem from various factors, including larger turbines and lower manufacturing costs. Solar power generation has made similar gains.

Innovations in these sectors proved complementary. Electricity from wind and solar technologies remain variable and present challenges for grid management because generation may not align with the demands of the electric grid in any given hour. Relative to most other sources of electricity, natural-gas-fired generators can quickly ramp up and ramp down generation to assist with grid integration and systems balancing requirements. Gains from innovation, however, have not occurred everywhere. Cellulosic biofuel production has grown slowly and is well below levels prescribed by a Federal mandate (see box 4-1).

Box 4-1. The Limits of Energy Mandates to Induce Innovation

The directness of government mandates can have great appeal. Commands that the market conform to government targets, however, have limits in what they can achieve, as illustrated by the Federal Renewable Fuel Standard. Even when targets are met, they can come at a much higher cost than projected.

Figure 4-i. U.S. Cellulosic Biofuel Statute and Final Volumes, 2010–19



Source: Congressional Research Service.

To further U.S. energy independence and provide additional revenue sources to U.S. farmers, the Federal Renewable Fuel Standard, which was set in 2005 and expanded in 2007, mandated increases in the domestic production and consumption of renewable fuels. The standard mandated the use of different categories of renewable fuels, with type-specific targets increasing over time for most categories. Technology to produce ethanol from corn was well established by the mid-2000s, and corn-based ethanol production and consumption quickly increased and have generally kept in line with the targets set in the 2007 statute. In contrast, technology to convert cellulosic plant material, such as corn fodder, into renewable fuels was not well established when the standard went into effect, and progress has been slow despite the mandate. As a result, the EPA has utilized its waiver authority, authorized in the 2007 statute, when setting targets for cellulosic biofuel (figure 4-i). The cellulosic mandate has been waived every year since its establishment in 2010, resulting in no significant production of cellulosic biofuel. By 2019, the industry was to have produced 8.5 billion gallons of cellulosic biofuel.

The Effects of Innovation on Productivity, Prices, and Production

Innovation raises productivity and lowers production costs, allowing firms to offer lower prices. This dynamic corresponds to the textbook case of an outward shift in the domestic supply curve, as shown in figure 4-1, for the case of natural gas. The shift means that firms produce more at every price level than they did before innovation, which lowers the market equilibrium price, which is shown on the vertical axis in figure 4-1 as a change in *P*, while increasing the quantity produced, as shown on the horizontal axis as the change in *Qp*. The lower price stimulates an increase in consumption, as shown on the horizontal axis as the change in *Qc*.

Because of imports and exports of natural gas, the market price is affected by the global price and does not occur at the intersection of domestic supply and domestic demand. Before shale gas development, domestic consumption exceeded domestic production, leading to imports, as shown in figure 4-1 as the difference between domestic production and consumption before shale. After shale, domestic production exceeds domestic consumption, leading to exports.

The Impact on Productivity

Horizontal drilling and hydraulic fracturing made the development of shale and other low-permeability formations economical. In the last decade, all growth in onshore oil and gas production has come from the development of these formations. One measure of innovation and productivity gains by energy producers is the quantity that new wells are producing relative to the number of rigs in use, which the DOE's Energy Information Administration (EIA) tracks for all major shale formations. This measure, known as new-well production per drilling rig, is defined as the total production of wells recently brought into production divided by the number of drilling rigs recently in operation.

New–well production per rig increased by more than 8-fold between 2007 and 2019 for key shale gas regions and by more than 19-fold for key shale oil regions. Particularly strong growth has occurred in the last five years for both oil and gas (figure 4-2).[3] The recent growth highlights how energy firms have continued to improve upon the earlier breakthroughs of shale pioneers.

The productivity gains in production per rig stem from several factors that allow firms to generate more production from each rig per unit time. For example, across regions and over time, the number of days needed to drill a

[3] The sharp rise in productivity in 2016 largely reflects firms deciding to operate fewer drilling rigs (because of very low prices) and focus on bringing wells already drilled into production. This can be seen by a sharp decline in drilled but uncompleted wells in 2016. Similarly, a rise in drilled but uncompleted wells in 2017 helps explain the apparent slowdown in productivity in that year. See EIA (2019) for estimates of drilled but uncompleted wells.

Figure 4-1. Innovation in Natural Gas Production

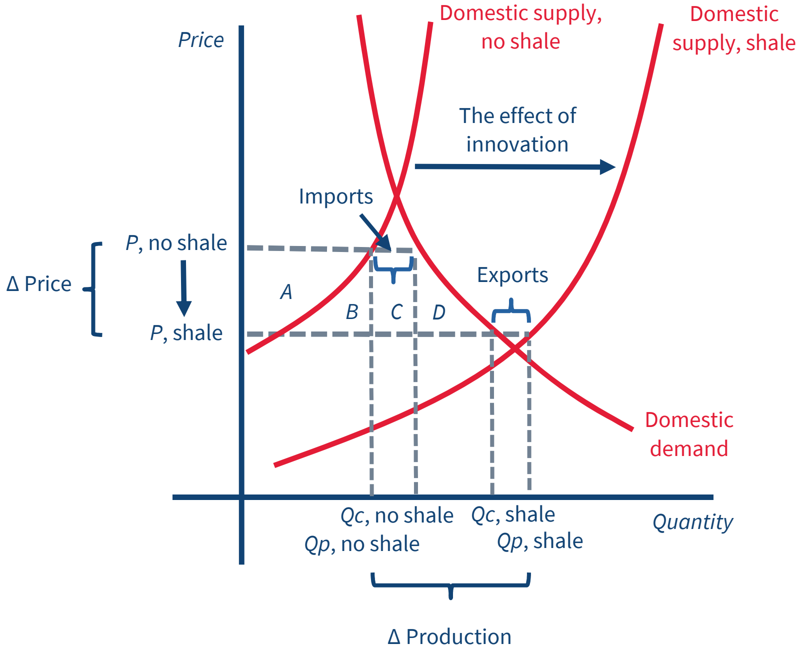
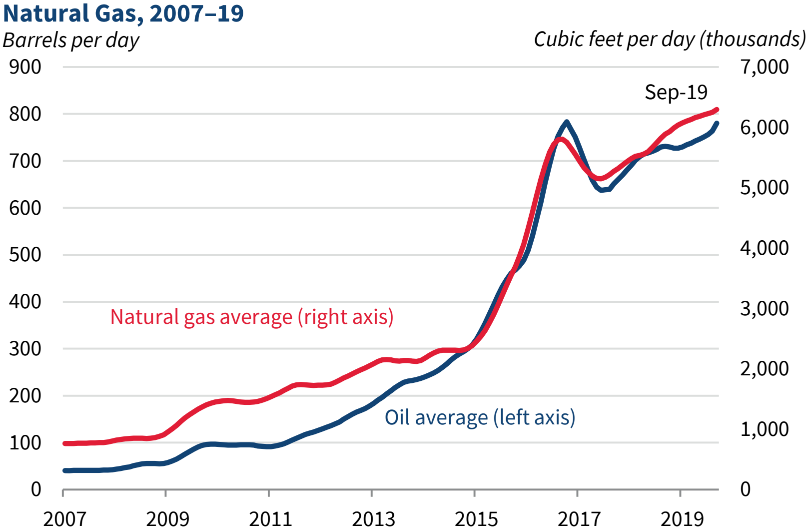
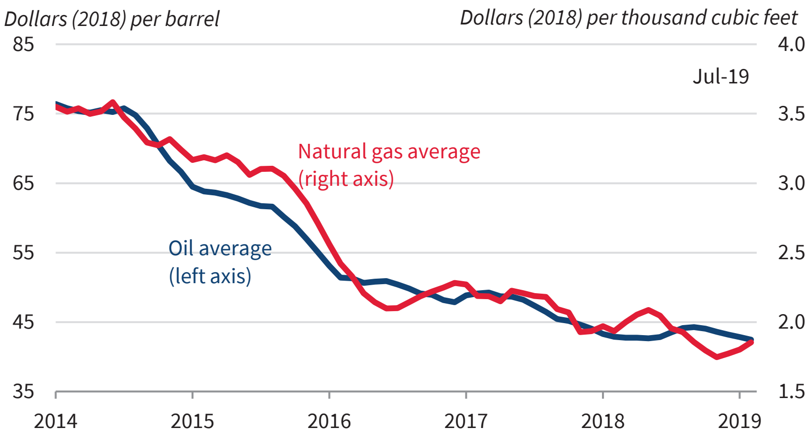


Figure 4-2. Productivity Gains: New-Well Production per Rig, Oil and Natural Gas, 2007–19



Sources: Energy Information Administration; CEA calculations.
Note: New-well production is the number of oil (or gas) wells, and their output, that are in their first month of production. The rig count is the number of active oil (or gas) drilling rigs two months prior.

Figure 4-3. Gains in Productivity Lower Breakeven Prices Across Key Shale Formations, 2014–19



Sources: Bloomberg; BTU Analytics; CEA calculations.
Note: Breakeven prices include the cost of drilling and operating a well and bringing the resource to market, including royalties, taxes, and gathering and compression costs. The oil average is the average price between Bakken Formation, Denver Basin, Eagle Ford, and Permian Basin. The natural gas average is the average price between Marcellus-Utica and Haynesville. Data, adjusted to 2018 dollars using the Consumer Price Index (CPI-U), are a six-month moving average.

well has fallen (EIA 2016), and the average production from a well's first month has grown (EIA 2018b). The improvements come partly from firms drilling wells with longer horizontal portions, and from placing more wells per pad—both of which allow each well and pad to access more oil and gas.

Greater productivity reduces the cost of producing each barrel of oil or cubic foot of natural gas. Lower unit costs lead to a lower breakeven price, which is the price needed to cover the costs of drilling and operating an oil or gas well. Figure 4-3 shows an estimated breakeven price based on modeling of production costs in different regions.[4] From 2014 to 2019, the breakeven price for natural gas (averaged across key shale formations) fell by 45 percent; for oil, it fell by 38 percent. The link between productivity—as measured by new-well production per rig in operation—and breakeven prices is direct. Well operators typically lease drilling rigs, paying as much as $26,000 per day, so finishing a well in half the time yields considerable savings. Similarly, higher volumes of initial production return cash more quickly to the firm and can mean greater lifetime production from the well.

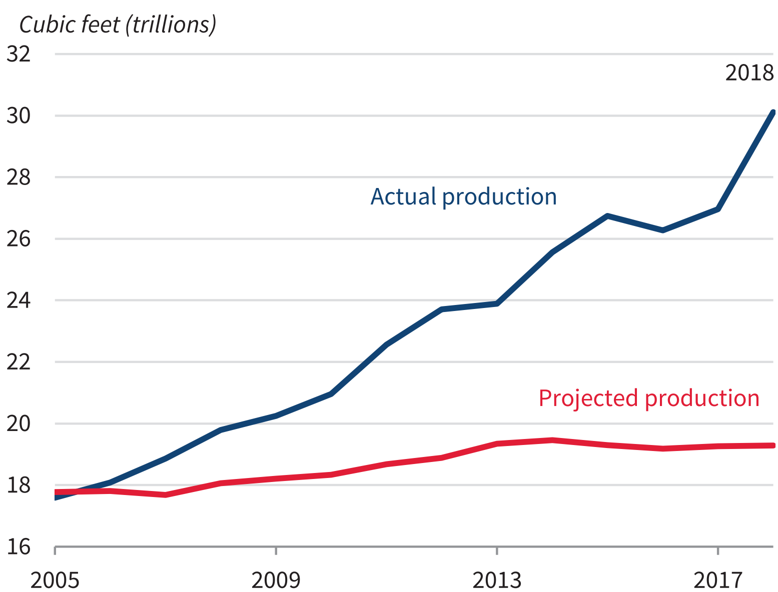
[4] The breakeven price, calculated by BTU Analytics, is best interpreted as the price needed to justify drilling another well, assuming that the energy firm already holds the necessary acreage. The price for a given period is calculated based on historical production data and projections of future production to model revenue and costs for every well brought into production in the period. This analysis assumes a discount rate of 10 percent and a well life of 240 months. It is not based on energy firm calculations of their own breakeven costs and excludes potential costs that energy firms may incur, such as interest payments on debt and costs to acquire their acreage.

The Impact on Prices and Production

In its *Annual Energy Outlook*, the EIA projects energy-related outcomes for the coming decades. The projections incorporate detailed information and assumptions on resource reserves, emerging technologies, new policies, and numerous other relevant trends. The difference between projected and actual outcomes provides one measure of the surprise and disruption brought by the shale revolution. This difference does not necessarily isolate the shale revolution's contribution because markets may have evolved differently than expected for reasons other than shale.

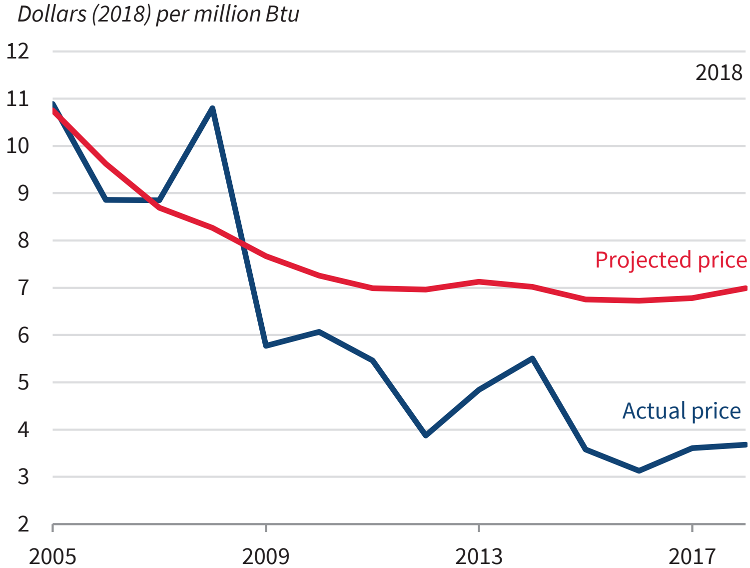
The 2006 *Annual Energy Outlook*, which made projections for 2005 and later, projected that natural gas production in the lower 48 States would rise gradually and reach 19 trillion cubic feet by 2018. Actual dry gas production for the lower 48 states reached more than 30 trillion cubic feet in 2018, 58 percent higher than projected, and now greatly exceeds that of any other country (figure 4-4). The production growth was not because of higher-than-expected prices. To the contrary, prices in 2018 were 46 percent lower than projected (figure 4-5).

Figure 4-4. Natural Gas Actual Production versus Projected Production, 2005–18



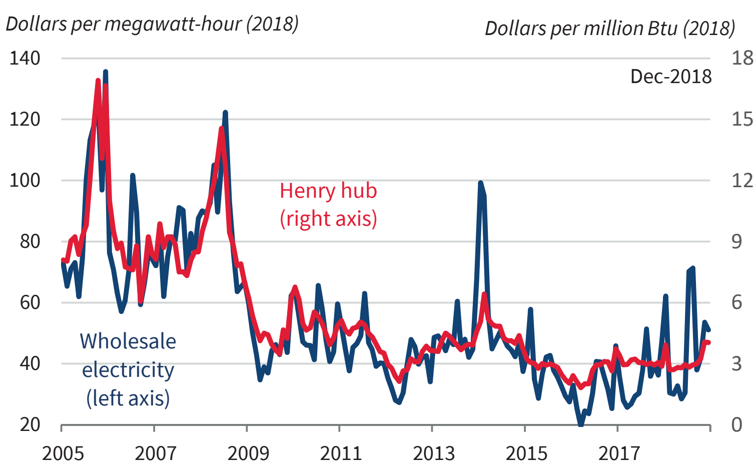
Sources: Energy Information Administration (EIA); CEA calculations.
Note: Projections are from the EIA *2006 Annual Energy Outlook*. Production is for the lower 48 States, which exclude Alaska and Hawaii. Dry gas refers to gas that is primarily methane, rather than hydrocarbon compounds.

Figure 4-5. Natural Gas Actual Prices versus Projected Prices, 2005–18



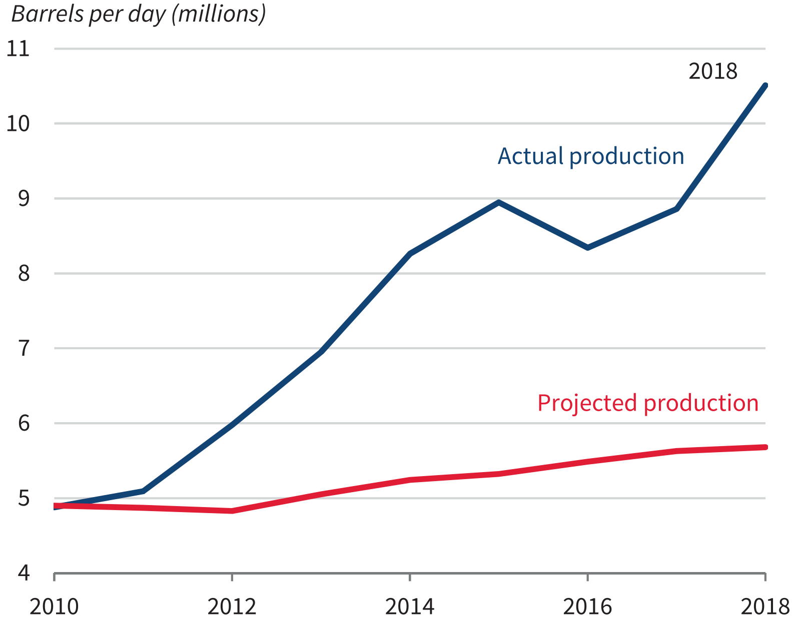
Sources: Energy Information Administration (EIA); CEA calculations.
Note: Btu = British thermal unit. Projections are from the EIA *2006 Annual Energy Outlook*. Prices are adjusted to 2018 dollars using the Consumer Price Index (CPI-U). Dry gas refers to gas that is primarily methane, rather than hydrocarbon compounds.

Figure 4-6. U.S. Monthly Wholesale Electricity Price and Natural Gas



Sources: Energy Information Administration; Intercontinental Exchange; CEA calculations.
Note: Btu = British thermal unit. Wholesale electricity prices were weighted by volume across weeks and eight wholesale electricity hubs. Wholesale natural gas prices are the Henry Hub spot price. Prices are adjusted to 2018 dollars using the Consumer Price Index (CPI-U).

Figure 4-7. U.S. Crude Oil Production, 2005–18

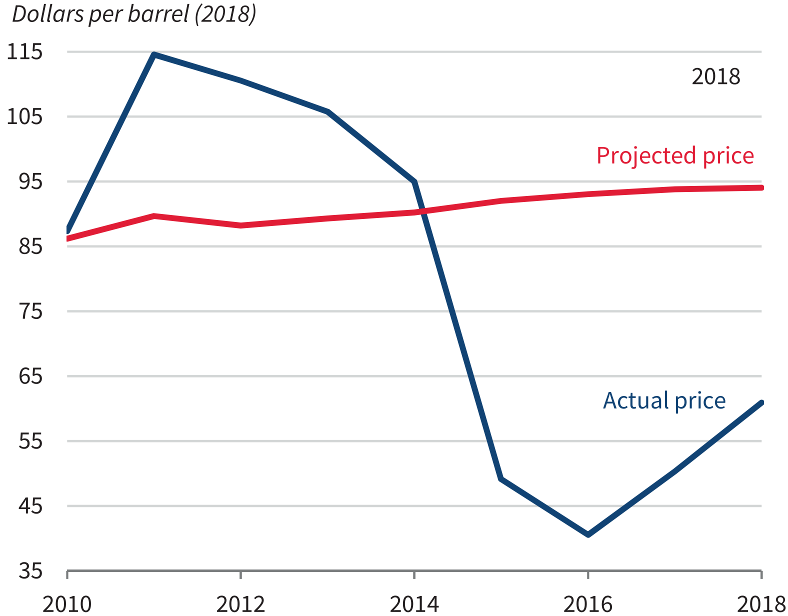


Sources: Energy Information Administration; CEA calculations.
Note: Projections are from the *EIA 2011 Annual Energy Outlook*. Production is for the lower 48 states, which excludes Alaska and Hawaii. Production includes both onshore and offshore production.

The unexpected production growth and price decline of natural gas spilled over to electricity markets. Wholesale electricity prices oscillated around $80 per megawatt–hour from 2005 to 2008, but then dropped markedly as the price of natural gas fell. Although natural gas-fired generators have accounted for less than one-third of electricity generating in recent years, they play an outsized role in influencing prices in competitive wholesale electricity markets. This is because such generators are often the marginal generator of electricity, and their operators can adjust output quickly in response to the market with relative ease, making their costs and bid prices an important determinant of the market price of electricity. Figure 4-6 shows the close tracking of wholesale natural gas and electricity prices, and several studies have documented a strong causal effect of natural gas prices on wholesale electricity prices (Linn, Muehlenbachs, and Wang 2014; Borenstein and Bushnell 2015).

Turning to oil, the difference between projected and actual oil production is even starker than the case of natural gas. Actual production in the lower 48 States in 2018 exceeded the production projected by the EIA in 2011 by 85 percent, leading the United States to surpass Russia and Saudi Arabia to become the top global oil producer. Some of the difference between actual

Figure 4-8. Imported Oil Prices, 2005–18



Sources: Energy Information Administration; CEA calculations.
Note: Projections are from the *EIA 2011 Annual Energy Outlook*. Prices are adjusted to 2018 dollars using the Consumer Price Index (CPI-U). Imported crude prices are the refiners' average acquisition cost for imported crude oil.

and projected production stems from greater-than-expected oil prices in the first half of the 2010–18 period. The benefit of oil sector innovation, however, is still evident; since 2015, actual prices have been below projected prices, while production has greatly exceeded projections (figures 4-7 and 4-8).

The Impact of the Shale-Induced Decline in Energy Prices

A simple supply-and-demand framework permits estimating how much energy prices have fallen because of the shale revolution as opposed to other factors that have changed over time. For natural gas, we draw from Hausman and Kellogg (2015), who look at the market effects of shale gas from 2007 to 2013. Their analysis focuses on estimating the price of natural gas in a world without the shale revolution, noting that the actual change in price before and after the emergence of shale is not necessarily the causal effect of shale because the demand curve could have shifted. As a result, they estimate supply and demand curves for natural gas for 2007 and for 2013. The price of natural gas in the no-shale scenario is then estimated as the price at the intersection of the 2007 supply (pre-shale) curve and the 2013 demand curve.[5] (For details on estimating the shale-driven price effect, see Hausman and Kellogg 2015). Our primary modifications to their price analysis are to use 2018, the most recent year for annual data, as the end year, not 2013; and to use more recent estimates of the supply elasticity of natural gas from Newell, Prest, and Vissing (2019).

We also estimate the effect of lower natural gas prices on wholesale electricity prices. Natural gas plays a unique role in the electricity sector. In many parts of the United States that have competitive wholesale electricity markets, natural-gas-fired plants generated the marginal unit of electricity sold. As a result, a decline in their costs lowers the market price of electricity, meaning that all electricity generators, regardless of their fuel source, receive a lower price. Likewise, all buyers, regardless of who provides their electricity, pay a lower price. Linn, Muehlenbachs, and Wang (2014) studied the effect of the shale-driven decline in natural gas prices on electricity prices and found that across wholesale market hubs, a 1 percent decrease in the price of natural gas lowers the price of electricity by 0.72 percent. To estimate the shale-driven change in the wholesale price of electricity, we therefore multiply the shale-driven percentage change in the price of natural gas (described in the prior paragraph) by 0.72.

For estimating the effect of shale oil on prices, we consider two surges in shale oil production, with the second surge associated with production cuts by the Organization of the Petroleum Exporting Countries (OPEC). The first wave is defined by Kilian (November 2008–August 2015), and the second we define as January 2017–May 2019. For the first wave, we draw from Kilian (2017), who estimates the monthly Brent crude oil price absent U.S. shale oil development. For the second wave, we take the Killian effect from the end of the first wave and apply it to the change in U.S. shale oil production in the second wave, after taking into account the production cuts among OPEC countries since 2016.

Kilian (2017) estimates the first shale oil wave reduced the global oil price by roughly $5.00 per barrel by August 2015. Extending his analysis to the second wave of production growth from shale, we estimate that the additional production further cut $1.29 per barrel by May 2019, resulting in a total price drop of $6.29 per barrel. This represents a 10 percent decline in the 2018 price of oil relative to what it would have been if the shale revolution had never occurred.

Turning to natural gas, we estimate that in a no-shale scenario, the price of natural gas would be $7.79 per thousand cubic feet, which is given by the

[5] Both prices are estimated by finding the price that solves a similar basic equation: Quantity Supplied (*P*) + Net Imports (*P*) = Residential Demand (*P*) + Commercial Demand (*P*) + Industrial Demand (*P*) + Electric Power Demand (*P*), where *P* is the price of natural gas. The demand and supply curves are assumed to take the form $Q = A \cdot (P + markup)^{\eta}$, where η is an elasticity. The net import function is assumed to be linear in price and is estimated using data from 2000 to 2018.

intersection of the 2007 natural gas supply curve and the 2018 demand curve. With the shale-driven outward shift in the supply curve, the price falls to $2.87 per thousand cubic feet, a 63 percent decrease. Put differently, natural gas prices in 2018 were 63 percent lower than they would have been if the shale revolution had never occurred, and they were far less variable. This is roughly the same percentage change in the Henry Hub price of natural gas over the 2007–18 period.

Based on the estimates by Linn, Muehlenbachs, and Wang (2014), the lower price of natural gas implies that shale gas led to a 45 percent decrease in the wholesale price of electricity as of 2018. This estimated decline is also consistent with the wholesale futures price data listed by the EIA from the Intercontinental Exchange. In real terms, the weighted-average wholesale price across market hubs fell by 44 percent from 2007 to 2018.

We note that retail electricity prices did not decline during the same period, in part because of State renewable portfolio standards mandating that a certain percentage of a State's electricity must come from renewable sources like wind or solar. At least 29 States have adopted such standards, with the first being Iowa in 1983. The most recent study of these standards finds that even modest renewable electricity targets bring considerable retail price increases (Greenstone and Nath 2019). They find that 12 years after a State adopted a renewable portfolio standard, retail electricity prices increased by an average of 17 percent. Over the same period, the standards raised the proportion of renewable electricity generation by at most 7 percentage points.[6]

Innovation-Driven Consumer Savings, Energy Independence, and Environmental Benefits

This section first explores methods of estimating consumer savings from lower energy prices. Then it examines the salient findings related to these consumer savings. Next, it delineates the United States' path toward energy independence. And finally, it discusses the environmental benefits of the shale revolution.

Consumer Savings—Methods

Lower energy prices can benefit consumers in diverse ways—through lower bills for heating or lighting, less spending at the gas pump, and lower prices for goods or services that require considerable energy inputs such as airline travel or building materials. The standard approach to estimating the total consumer

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[6] This assumes that the state started with zero renewable electricity generation, which is why it is a generous estimate of the increase in renewable generation caused by the standard. The 7 percent is based on the finding by Greenstone and Nath (2019) that the gross renewable requirement increased to roughly 11 percent 12 years after adopting a standard and that the actual level of renewable generation was about 4 percentage points below the grow requirement.

benefit from a price decline is to calculate the savings for those consuming before the price decline, whose value is represented in figure 4-1 above by the rectangle formed by areas *A*, *B*, and *C*, and the savings on additional consumption spurred by the price decline, represented by area *D*.[7] We take this approach for oil, multiplying the shale-induced change in the price of oil ($6.29 per barrel) with the pre-shale quantity consumed (about 7.0 billion barrels annually), and adding it to one-half the product of the price change and the price-induced change in consumption (0.1 billion barrels).

We modify this approach for natural gas to account for the spillover effects in the electricity market. First, we estimate savings using the standard approach described above and following Hausman and Kellogg (2015), who break total demand into its sectoral components, including the electricity sector. We first estimate savings for the electric power sector in the same manner as Hausman and Kellogg (2015); call this S^{HK}. Their approach assumes that each $1 saved because of cheaper natural gas translates into $1 saved for electricity consumers. This is a reasonable approach for the share of the power sector with cost-of-service regulation, in which case regulators would only reduce compensation to natural-gas-fired generators, not to other generators, and only by as much as such generators had cost reductions.

For the share of the sector without cost-of-service regulation, however, we translate the lower natural gas prices into lower wholesale electricity prices, following Linn, Muehlenbachs, and Wang (2014). The price-setting effect of natural-gas-fired electricity generators magnifies the effect of lower natural gas prices because the gas-driven decline in wholesale electricity prices applies to all electricity consumed in deregulated markets, not just the electricity generated by natural gas. We then assume that wholesale market savings pass through to retail savings, dollar for dollar, which is consistent with the research of Borenstein and Bushnell (2015), who find high rates of pass-through in deregulated markets.

One-third of the electricity generated in the United States in 2018 was generated in States without cost-of-service regulation of generators.[8] Based on this share, we estimate total electric power sector savings to be the sum of the savings in regulated markets (= 0.67 x S^{HK}) and the savings from unregulated markets (= 0.33 x $S^{Wholesale}$).

[7] The supply shift and price change will also affect producer surplus (not shown in figure 4-1), which is the difference between revenue and cost across all units produced and all producers. Whether producers benefit from innovation (as measured by producer surplus) depends in large part on how much prices fall and quantities increase. It is likely that there is a net loss in producer surplus for natural gas producers (Hausman and Kellogg 2015) but a gain for oil producers, whose production has increased greatly with only a modest price decline.

[8] The EIA provided the CEA with an analysis of data from EIA Form 923, which collects detailed information from the electric power sector. The analysis showed that in 2018, 33 percent of electric power supply occurred in regional transmission organizations in unregulated states.

The approach to estimating natural gas savings, which involves sector-specific consumption amounts and demand curves, permits calculating savings for the residential, commercial, industrial, and electric sectors, which we collapse into two sectors: the nonelectric sector and the electric sector. For oil, we break savings into transportation and nontransportation sector savings, allocating savings to the transportation sector based on its share of total petroleum consumption in the United States (70 percent) as reported by the EIA for 2018.

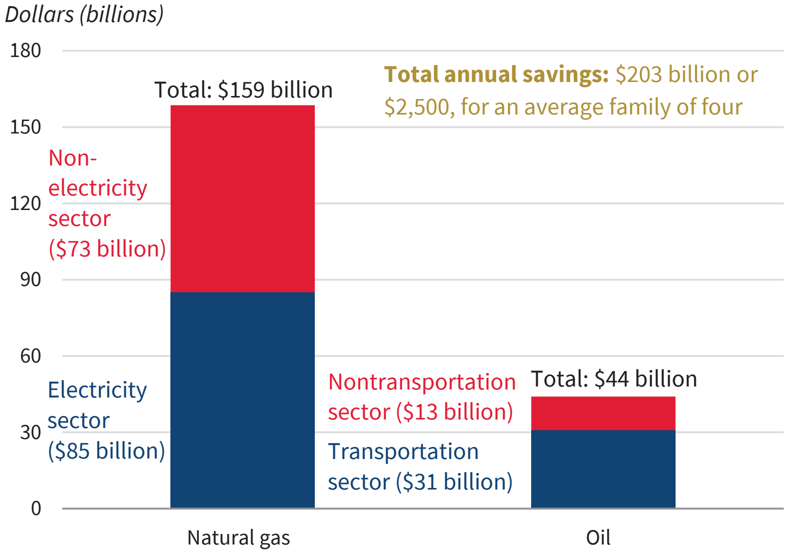
Regarding the pass-through of energy savings to household income groups, we first allocate residential natural gas and residential electricity savings based on each income group's share of spending on natural gas and electricity, as reported in the 2018 Consumer Expenditure Survey of the Bureau of Labor Statistics. We then estimate the oil-related transportation sector savings associated with direct household consumption by multiplying the total oil savings by the share of transportation sector energy use accounted for by light-duty vehicles such as cars and sport utility vehicles. These direct household savings are then distributed to household income groups based on each group's spending on "gasoline, other fuels, and motor oil," as reported in the 2018 Consumer Expenditure Survey.

Finally, we allocate the natural gas, electricity, and oil-related savings that initially occur in the commercial and industrial sectors. We assume that the savings are eventually passed through to households in the form of lower product prices, with savings allocated to each household income group according to its share of total household expenditures, as reported in the 2018 Consumer Expenditure Survey. This is a common approach in the literature on the incidence of carbon taxes, which increase energy prices (Mathur and Morris 2014). It also has empirical support in important product markets (e.g., Muehlegger and Sweeney 2017). The exporting of some of the industrial sectors' output to global markets would suggest that the approach overstates savings to U.S. consumers. The shale revolution, however, has also reduced global energy prices, which would lower the costs of foreign producers, some of whom serve the U.S. market. We assume that these competing effects offset each other.

Consumer Savings—Findings

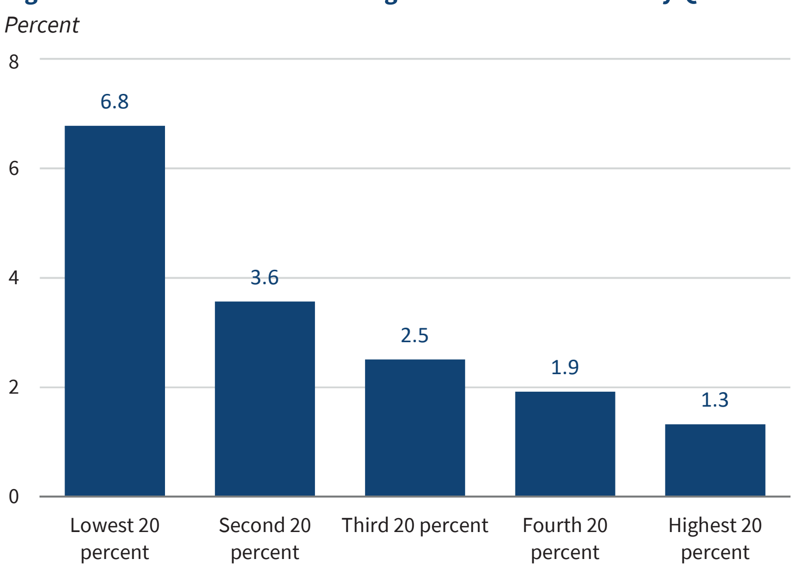
By lowering energy prices, the shale revolution is saving U.S. consumers $203 billion annually, or an average of $2,500 for a family of four. Nearly 80 percent of the savings stem from a substantially lower price for natural gas, of which more than half comes through lower electricity prices (figure 4-9). The large decline in the price of natural gas, and therefore large savings, is because domestic supply has overwhelmed domestic demand, and the capacity to liquefy and export natural gas to global markets has expanded too slowly to absorb the supply growth. Oil, in contrast, is economical to transport and is traded on a

Figure 4-9. Shale Oil and Gas Consumer Savings per Year by Sector



Sources: Energy Information Administration; Kilian (2016); Caldara et al. (2019); CEA calculations.

Figure 4-10. Total Consumer Savings as a Share of Income by Quintile



Sources: Bureau of Labor Statistics; CEA calculations.
Note: Values represent the CEA's estimates of consumer savings as a share of pretax income in 2018.

Box 4-2. Economic Effects Linked to Drilling and Production

Although much of this chapter focuses on the shale revolution's effect on consumers, growth in drilling and production has also brought employment, income, and public revenues to producing regions and beyond. Relative to the State of New York's border counties, which have not had shale development, Komarek (2016) found that counties in the Marcellus region that were developed had a 6.6 percent increase in earnings. Across the United States, Feyrer, Mansur, and Sacerdote (2017) estimate that new extraction increased aggregate employment by as much as 640,000 jobs. In addition to creating wage-earning opportunities, expanded drilling in places like North Dakota and Pennsylvania has also brought large payments to landowners holding rights to subsurface resources. Energy firms typically compensate resource owners by paying them a share of the value of production from their land. In 2014, production from major shale formations generated nearly $40 billion in payments to resource owners (Brown, Fitzgerald, and Weber 2016).

Drilling and production can also generate revenue for some State and local governments and local school districts. Between 2004 and 2013, State revenues from taxes on oil and gas production in the lower 48 states nearly doubled, reaching $10.3 billion in real terms (Weber, Wang, and Chomas 2016). At the local level, increases in revenues have largely outweighed costs for local governments in most producing states (Newell and Raimi 2018). In certain states, such as Texas, oil and gas wells are also taxed as property and can therefore provide revenues to local school districts. For example, shale development in Texas's oil formations increased the property tax base by over $1 million per student in the average shale district, leading to 20 percent more spending per student (Marchand and Weber 2019).

massive global market, which domestic oil production has influenced but not overwhelmed. As a result, oil accounts for the other 20 percent of the savings, most of which are transportation sector savings on fuel.

Because lower-income households spend a larger share of their income on energy bills, the savings have greater relative importance for them. Energy savings represent 6.8 percent of income for the lowest fifth of households, compared with 1.3 percent for the highest fifth (figure 4-10). In other words, lower energy prices are like a progressive tax cut that helps the lowest households the most. The variation in savings stems heavily from differences in spending on electricity; according to the 2018 Consumer Expenditure Survey, the bottom 20 percent of households account for 8.6 percent of expenditures in general but for 14.1 percent of electricity expenditures. We also considered the economic benefits of increased drilling and production on employment, income, and public revenues in differing regions as well (box 4-2).

Energy Independence

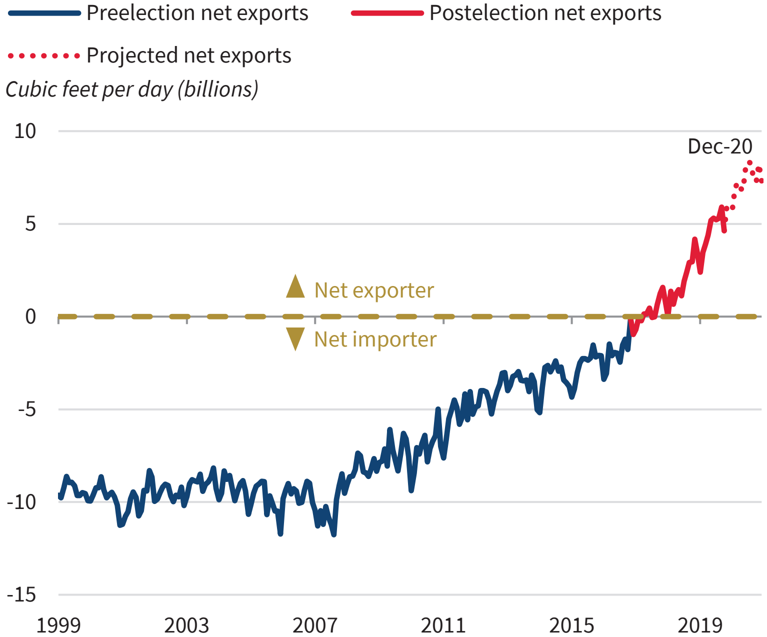
Historically, a rise in energy prices increases the trade deficit and costs for firms and households, sometimes pushing the U.S. economy into a recession. For example, a sudden rise in the price of oil preceded 10 of the 11 postwar recessions in the United States (Hamilton 2011). The vulnerability of the U.S. economy to price shocks motivated a long-standing goal of U.S. Presidents: U.S. energy independence.

President Richard M. Nixon began the push for energy independence, announcing Project Independence in 1973 when the Organization of Arab Petroleum Exporting Countries halted oil shipments to the United States. In the ensuing years, Congress and the executive branch directed much attention and resources to pursue energy independence, including the Energy Policy and Conservation Act (1975), the establishment of the Department of Energy (1977), the Energy Policy Act (2005), and the Energy Independence and Security Act (2007).

By a common measure of independence—net exports (Greene 2010)—the United States essentially achieved independence in both natural gas and oil at the end of 2019, and net exports are projected to grow in 2020 and beyond. Today's achievement, however, does not stem primarily from these government efforts but rather from private sector innovation that few expected. The shale-driven growth in domestic production documented earlier in this chapter reduced imports and, most recently, led to a surge in exports of both oil and gas. Fewer imports and more exports caused U.S. net imports of natural gas to fall below zero in 2017, making the United States a net exporter of natural gas for the first time since 1957 (figure 4-11). And, in September 2019, net imports of crude oil and petroleum products fell below zero on a monthly basis (figure 4-12). The United States is projected to remain a net exporter of crude oil and petroleum products for all of 2020 for the first time since at least 1949.

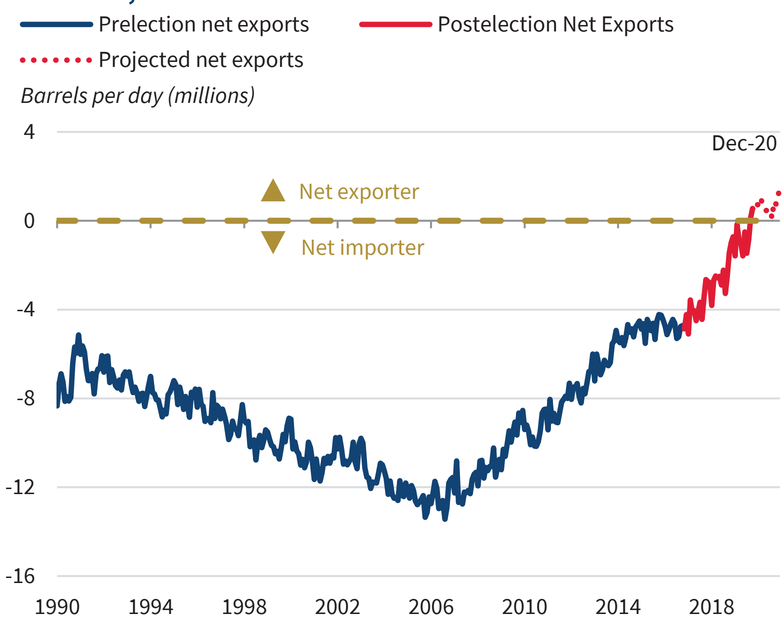
Energy independence—as measured by positive net exports, and by increased sectoral diversification of the U.S. economy, especially in places like Texas—means that higher global energy prices have a negligible or perhaps positive effect on the U.S. economy in the aggregate. With a large domestic energy sector, increases in investment by the domestic energy sector offset the effect of higher prices on consumers (Baumeister and Kilian 2016). If, for example, higher oil prices induce substantial new investment in drilling wells, with its associated demands for steel and equipment, GDP would likely increase as long as the reduced disposable income of consumers has a small effect on their overall spending (see box 4-2 for an in-depth explanation of the economic impact of increased drilling and production). This does not mean that the typical U.S. consumer is unaffected by higher oil prices or benefits from them. Rather, it means that the country's total output may expand as prices rise.

Figure 4-11. U.S. Monthly Net Exports of Natural Gas, 1999–2020



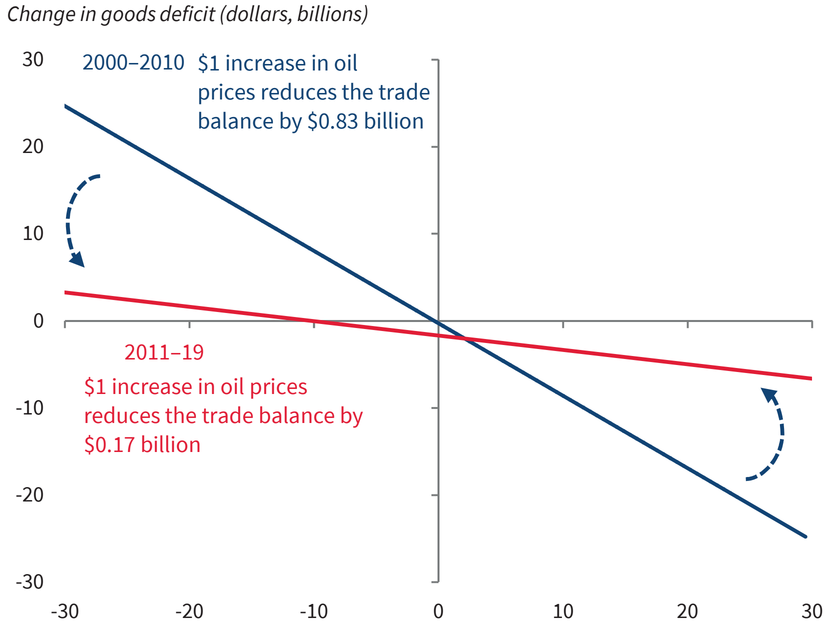
Sources: Energy Information Administration; CEA calculations.

Figure 4-12. U.S. Monthly Net Exports of Crude Oil and Petroleum Products, 1990–2020



Sources: Energy Information Administration; CEA calculations.

Figure 4-13. Changes in Price of Oil (Prior Month) and Changes in the Goods Trade Balance, 2000–2010 and 2011–19



Sources: Energy Information Administration; *Wall Street Journal*; Census Bureau; CEA calculations.

In addition, if net imports are near zero, large changes in the global price of oil will have negligible effects on the U.S. trade balance, which directly affects the country's GDP (Cavallo 2006). Figure 4-13 shows that over the 2000–10 period, when the United States imported record amounts of oil and petroleum products, a $1 per barrel increase in the price of oil reduced the trade balance in goods by $0.83 billion. In the 2011–19 period, which saw falling net imports, the same price increase reduced the trade balance by only $0.17 billion. As U.S. net exports increase, higher prices should eventually increase the trade balance, reflecting greater transfers from foreign consumers to domestic producers.

Energy independence also brings geopolitical benefits, such as more influence abroad and fewer constraints on foreign policy. The rise of the United States as a net contributor to the global oil market has reduced oil prices (Kilian 2016), and has also reduced the dependence of the global market on particular producers. Currently, the United States has sanctions on two major oil-producing countries, Iran and Venezuela. These sanctions, combined with internal factors in the case of Venezuela, have taken millions of barrels of oil per day off the market. Since the United States announced sanctions in November 2018, Iranian exports have declined by 1.4 million barrels per day, an 89 percent decrease from their pre-sanction level; since sanctions on Venezuela took effect in January 2019, exports have fallen by 0.7 million barrels per day, a 60 percent decrease. Energy independence increases the feasibility of such sanctions. In addition, it reduces the incentive to expend foreign policy resources on efforts to lower global energy prices.

Geopolitical gains also stem from net exports of U.S. natural gas. For example, exports of U.S. LNG to Europe have and will continue to provide a diversified source of competitively priced natural gas to reduce the continent's dependence on Russian gas supplies. The U.S. share of Europe's total natural gas imports increased from 0.1 percent in the first five months of 2018 to 1.3 percent in the first five months of 2019. The potential for greater exports of U.S. natural gas to Europe gives U.S. leaders greater influence when discouraging them from supporting the controversial new Nord Stream 2 pipeline project from Russia to Germany. Poland's and Lithuania's leaders are the most recent heads of state to denounce the project as a threat to energy security that would increase European dependence on Russian natural gas supplies.

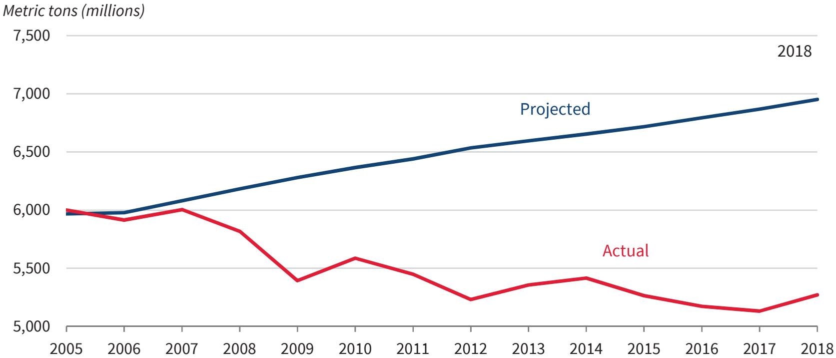
Environmental Benefits

In addition to bringing energy independence and saving the average family of four $2,500, the shale revolution has brought several environmental benefits. The shift to generating more electricity from natural gas and renewable energy sources reduced energy-related carbon dioxide emissions at the national level to a degree that was not predicted before these innovations. In its 2006 *Annual Energy Outlook*, the EIA projected a 16.5 percent *increase* in carbon dioxide emissions from 2005 to 2018 (figure 4-14). Actual emissions *decreased* by about 12 percent.

Actual energy-related carbon emissions for 2018 were 24 percent lower than projected in 2006. Some of the decline is because projections assumed greater GDP growth and therefore greater electricity demand than what actually occurred, in part because of the Great Recession and slow recovery. An important part of the decline, however, stems from lower natural gas prices reducing reliance on electricity generated from coal. Over the period, the proportion of generation from coal-fired power plants fell from 50 percent to 28 percent, while the share from natural gas increased from 19 percent to 35 percent.

Low natural gas prices also aided growth in the generation of wind power, which expanded from less than 1 percent of generation to 7 percent. Although Federal and State policies, such as renewable portfolio standards and tax credits, contributed to the increase in wind power generation, Fell and Kaffine (2018) document the important role of lower natural gas prices in spurring greater market penetration by wind generation. The complementarity stems from the ability of natural gas generators to quickly ramp up or slow down in response to the intermittent wind generation from gusts or lulls in wind.

Figure 4-14. Actual versus Projected Carbon Dioxide Emissions, 2005–18



Source: Energy Information Administration (EIA).
Note: Carbon dioxide emissions represent total emissions from the consumption of energy as reported by the EIA. Projections are from the EIA 2006 *Annual Energy Outlook*.

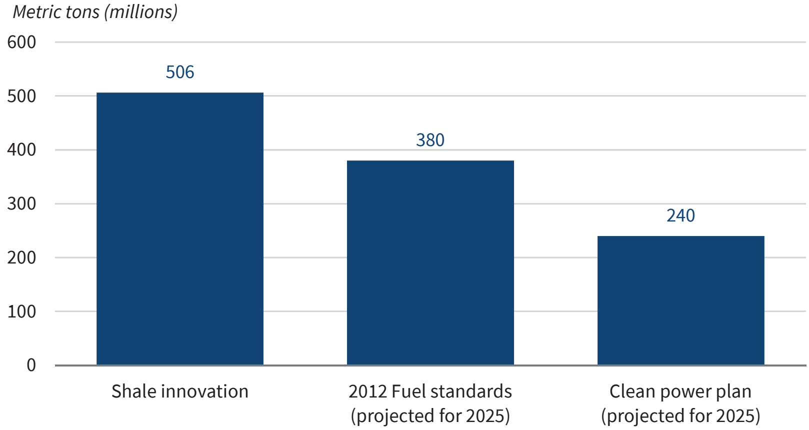
We estimate that from 2005 to 2018, the shale revolution lowered annual electric power carbon dioxide emissions by 506 million metric tons, a 21 percent decline relative to electric power sector emissions in 2005 (figure 4-15). For the estimate, we assume that coal emissions in the electricity sector would have otherwise remained constant, and we calculate the observed decline in coal emissions, which is 833 million metric tons. We assume that 92 percent of the decline is from shale-driven decreases in natural gas prices. This percentage is from Coglianese, Gerarden, and Stock (2019), who estimate the share of the decline in coal use attributable to the decline in the price of natural gas relative to the price of coal apart from other factors such as environmental regulations, which accounted for another 6 percent of the decline.[9] Finally, we subtract the increase in emissions from greater use of natural gas in electricity generation (506 million metric tons = 833 x 0.92 – 260).[10]

The shale-driven reduction in electric power emissions is larger than what the U.S. Environmental Protection Agency (EPA) projected its 2012

[9] Note that the decline in coal use and coal emissions is linked to the decline in the price of natural gas relative to the price of coal, not to the number of coal plants that are replaced with natural gas plants. Natural-gas-driven changes in electricity prices have caused coal plants to close, and the retired generation capacity has been replaced with a mix of natural gas plants and renewable sources. Also, we note that Coglianese, Gerarden, and Stock (2018) look explicitly at coal production, not consumption, but the two are similar. Over most of their study period, more than 90 percent of production was consumed domestically.

[10] A more detailed analysis could be done to estimate the net greenhouse gas (GHG) effects from shale gas. For example, the CEA estimate does not include leaks from natural gas wells or pipelines. According the EPA's emissions inventory, total GHG emissions from natural gas systems declined from 2005 to 2017. Alvarez et al. (2018) estimate that emissions are 60 percent greater than what the EPA reports. Even if this were true for the 2005 and 2017 EPA measurements, emissions from natural gas systems would have still declined over the period. If emissions were understated in 2017 but not in 2005, the shale-driven declines in emissions would still be larger than those from the policies mentioned in figure 4-15. In general, innovation in leak detection has lowered leak rates over time (see box 4-3).

Figure 4-15. Annual GHG Emission Reductions from Shale Innovation and Major Environmental Policies



Sources: Environmental Protection Agency; Stock (2017); CEA calculations.
Note: The Fuel Standards refer to the 2012 Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, which applied to the 2017–25 period.

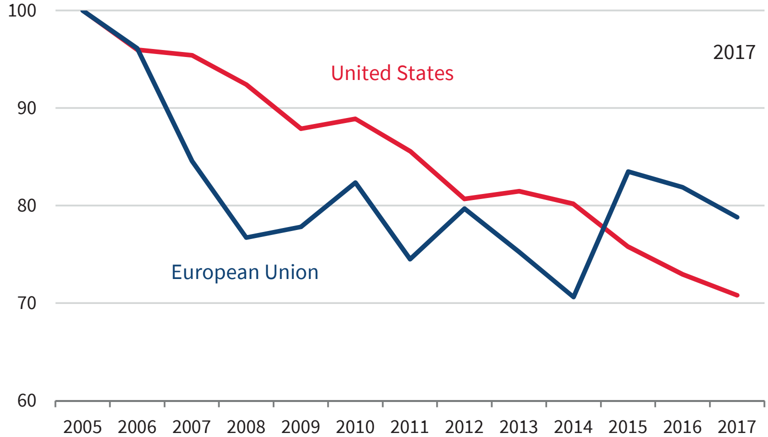
Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards would achieve in 2025 (380 million metric tons) following a considerable increase in stringency. The shale reduction is also more than double what the EPA initially projected that the now-rescinded Clean Power Plan would achieve by 2025 (240 million metric tons).

The shale-driven decline in emissions allowed the United States to have a greater rate of decline in total greenhouse gas (GHG) emissions than the European Union, holding constant the size of the two economies (figure 4-16). From 2005 to 2019, the European Union has developed and expanded an increasingly stringent cap-and-trade system for GHG emissions across its member countries. Although it substantially raised electricity prices for consumers (Martin, Muuls, and Wagner 2015), the system helped the European Union achieve a 20 percent decline in GDP-adjusted emissions from 2005 to 2017, the most recent year of data. Over the same period, emissions fell by 28 percent in the United States, which did not implement a national cap-and-trade system, although various States have pursued policies to cap emissions.

If policymakers had averted the shale revolution through a ban on hydraulic fracturing or other integral components of shale development, energy sector GHG emissions would most likely be higher today. Absent low natural gas prices, renewable electricity sources are unlikely to have enabled similar emissions reductions. A megawatt-hour of coal-fired electricity generates about 1 metric ton of GHG emissions. Achieving the 506 million metric ton decline in GHG emissions is roughly equivalent to reducing coal-fired electricity generation by about 506 million megawatt-hours and replacing it with renewable power generation. This amounts to a 150 percent increase in wind and

Figure 4-16. U.S. versus EU GDP-Adjusted Carbon Dioxide Emissions, 2005–17

Metric tons of CO_2 per billion dollars of GDP (2005 = 100)



Sources: Environmental Protection Agency; Bureau of Economic Analysis; European Environment Agency; Statistical Office of the European Communities; CEA calculations.
Note: Data are total CO_2 emissions per $1 billion (2017) of each region's GDP.

solar generation above their 2018 level, an increase that is not projected to happen until the 2040s.[11]

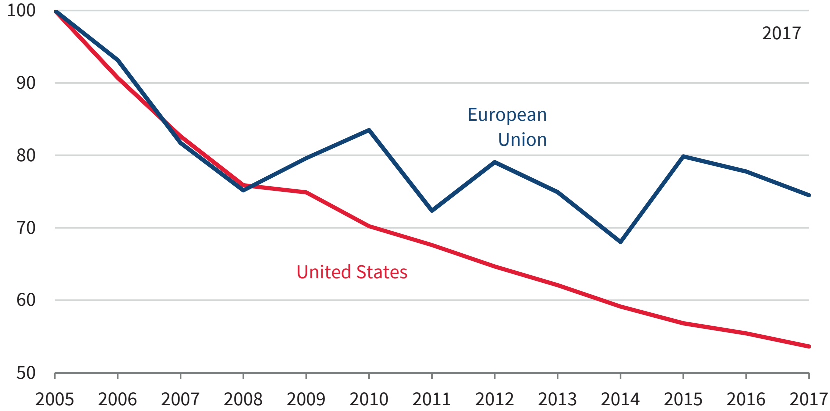
During the shale era, the percentage decline in coal-fired generation has roughly equaled the percentage decline in the wholesale price of electricity, suggesting that prices would need to fall 25 percent below their pre-shale level to reduce coal generation by 506 million megawatt-hours (25 percent). This decline would leave wholesale electricity prices about one-third above their 2018 level. This higher price is unlikely to have supported a 150 percent increase in wind and solar generation over their 2018 level (and an even larger percentage increase over their pre-shale level). It implies an elasticity of supply close to 5, roughly twice as large as the empirical estimate by Johnson (2014).

Shale-driven declines in emissions have been large as well as economical. Many policies seek to reduce emissions. Most of them, however, impose a cost on the economy. Gillingham and Stock (2018) summarize research on the cost of reducing a ton of carbon emissions by various methods. They report that renewable fuel subsidies cost $100 per ton of carbon abated, Renewable Portfolio Standards cost up to $190 per ton, and vehicle fuel economy standards cost up to $310 per ton. By comparison, shale innovation brings emissions savings without requiring greater public spending (e.g. subsidies) or costly regulations or mandates.

[11] The year 2046 is estimated using the EIA's 2019 *Annual Energy Outlook* forecast of wind and solar generation in the electric power sector through 2050 (EIA 2019c).

Figure 4-17. U.S. versus EU GDP Adjusted Particulate Emissions, 2005–17

Particulate tons per billion dollars of GDP (2005 = 100)



Sources: Environmental Protection Agency; Bureau of Economic Analysis; European Environment Agency; Statistical Office of the European Communities; CEA calculations.
Note: Values are total particulate matter emissions that are 2.5 microns or less in size per billion 2017 U.S. dollars of each respective region's GDP. Values are normalized such that 2005 is equal to 100. U.S. emissions exclude miscellaneous sources.

Lower natural gas prices have also affected emissions of particulates such as soot, which can affect heart and lung health, especially for those with asthma or heart or lung disease. As with GHG emissions, GDP-adjusted particulate emissions have declined faster in the United States than in the European Union over the 2005–17 period (figure 4-17). The difference in the rate of reduction is considerable, with U.S. particulate emissions per $1 of GDP declining by 57 percent and EU emissions declining by 41 percent. The decline has brought health benefits. Johnsen, LaRiviere, and Wolff (2019) estimate that, as of 2013, the shale-driven decline in particulate and related emissions had $17 billion in annual health benefits (see box 4-3).

The Value of Deregulatory Energy Policy

This section explores the value of deregulatory energy policy. First, it shows how deregulation allows innovation to flourish. Then it explains the private sector's part in the critical responsibilities of building and maintaining energy infrastructure.

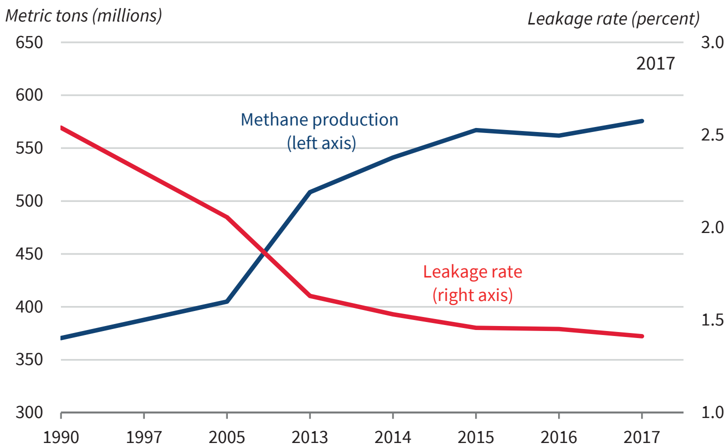
Allowing Innovation to Flourish

Government deregulation of natural gas markets—including the 1978 Natural Gas Policy Act, the Federal Energy Regulatory Commission's 1985 Open Access Order, and the 1989 Natural Gas Wellhead Decontrol Act—helped encourage

Box 4-3. Innovation in Pipeline Leak Detection

Pipelines are one of the most effective methods of transporting oil and gas, but they require monitoring and maintenance. Traditionally, monitoring has required that people travel along pipelines by foot, automobile, plane, or all-terrain vehicle. Innovation in technologies such as drones and advanced acoustics has allowed the industry to prevent leaks and more quickly find and stop them when they occur. For example, a Shell pilot drone program illustrates how well-equipped drones can identify pipeline corrosion, abnormal heat signatures, and any effects on wildlife. This helps the company identify leaks, but also reveals areas where preventive maintenance is most needed. With improvements to technology for monitoring pipeline leaks and other improvements across the supply chain, the leak rate for natural gas and petroleum systems fell 31 percent from 2005 to 2017 (figure 4-ii).

Figure 4-ii. Methane Production and Leakage Rates, 1990–2017



Sources: Environmental Protection Agency; Energy Information Administration; CEA calculations.
Note: The leakage rate was calculated by assuming that wellhead gas is about 85 percent methane by volume and assuming that the methane density is 0.0447 pounds per cubic foot.

the innovation that brought the shale revolution. In the same vein, the Trump Administration has sought to identify and remove regulations that unduly stifle energy development. This is seen in the Presidential Executive Order on Promoting Energy Independence and Economic Growth and the Executive Order on Promoting Energy Infrastructure and Economic Growth. It is also seen in actions such as permitting for the Keystone XL Pipeline and the DOE's approval of a record amount of Liquefied Natural Gas export capacity to non–free trade agreement countries.

The laboratory of State policy experiments provides examples of contrasting policy approaches and their effects. State governments have the primary responsibility to regulate oil and gas development on non-Federal lands, specifying where wells can be drilled, how they must be drilled and monitored, and how they are to be reclaimed at the end of their useful life. Subject to such regulations, most States allow shale development. Maryland, Vermont, and New York, however, have banned hydraulic fracturing, a practice integral to shale development. Of the three States, the New York ban is most consequential because the Marcellus Shale formation, which is the most prolific shale gas formation in the United States, extends into much of Southern New York. Since New York's initial 2010 moratorium on fracking, which morphed into a ban in 2014, energy firms have drilled more than 2,500 wells in Pennsylvania counties adjacent to the New York border (see box 4-4 for further discussion on the risks and benefits of shale development).

The difference in energy-related outcomes in the two States is stark. Development of the Marcellus and Utica Shale in Pennsylvania caused natural gas production to increase 10-fold from 2010 to 2017. Over the same period, New York's production fell by nearly 70 percent. Pennsylvania leads the country in net exports of electricity to other States and produces more than twice the amount of energy it consumes. New York, in contrast, has grown more dependent on electricity generated elsewhere; and in 2017, the State consumed four times as much energy as it produced.

Despite the growth in energy production in Pennsylvania, total energy-related carbon dioxide emissions fell 15 percent from 2010 to 2016, the most recent year of data, twice as much as in New York (7 percent). The greater decline in Pennsylvania stems from larger reductions in the electric power sector.

Innovation, however, can create challenges for particular sectors. Despite substantial and sustained Federal support, including a mid-2000s expectation of a nuclear renaissance, low wholesale electricity prices have reduced the profitability of the nuclear power sector. As a result, a wave of early retirements from existing nuclear power plants has occurred, with more closures planned in coming years (CRS 2018). Given that changes in the market are impossible to predict, a diversified research-and-development portfolio for new energy technologies will best prepare the economy for tomorrow's market realities.

The Critical Role of Energy Infrastructure

Pipelines, electric transmission lines, and export facilities allow energy resources to flow from resource-rich places to resource-scarce ones. The growth in oil and gas supply documented above increases demand for pipelines. For example, with a dramatic rise in production over the last decade,

Box 4-4. Shale Development and Local Communities

Many academic studies have explored the effects of shale oil and gas development on nearby communities. Two studies estimate measures of local net benefits across all major shale regions and reach a similar conclusion: on average, local wage and income effects from development exceed increases in living costs or deterioration in local amenities (Bartik et al. 2019; Jacobsen 2019). Jacobsen (2019) finds that wages across all occupations increased in response to the growth in drilling, regardless of whether they had direct links to the oil and gas industry. Similarly, Bartik and others (2019) estimate that shale development generated $2,500 in net benefits to households in surrounding communities.

It is also evident that local effects can vary greatly, which is illustrated in the diverse effects of development on housing values. Housing values reflect an area's standard of living, including earnings opportunities and amenities, such as good roads. Shale development affects both, creating jobs but also truck traffic and associated disamenities, particularly during times of drilling (Litovitz et al. 2013; Graham et al. 2015). In addition, development, when poorly managed, can pose a risk to groundwater and health, and improper disposal of wastewater can induce earthquakes when best management practices are not followed (Darrah et al. 2014; Keranen et al. 2014; Wrenn, Klaiber, and Jaenicke 2016; Hill and Ma 2017; Currie, Greenstone, and Meckel 2017). Development has had large, positive effects on average housing values over time in many places (Boslett, Guilfoos, and Lang 2016; Weber, Burnett, and Xiarchos 2016; Bartik et al. 2019; Jacobsen 2019). Drilling itself, however, has depressed property values, at least temporarily, for groundwater-dependent homes in Pennsylvania or properties without mineral rights in Colorado (Muehlenbachs, Spiller, and Timmins 2015; Boslett, Guilfoos, and Lang 2016). Welfare effects can also vary across households in shale areas based on the value that households place on greater earning opportunities relative to disamenities, such as noise and congestion.

The nuisances and risks that can come with drilling and fracturing wells highlight the value of prudent State and local policies that match local realities, safeguard the environment and human health, and allow private landowners to contract with energy firms to bring valuable energy resources to market. Almost all major producing States have revised oil and gas laws to address hydraulic fracturing and shale development more generally. North Dakota, for example, adopted rules limiting the flaring of natural gas in 2014, a practice that is especially common in the State because oil producers there have limited infrastructure to deliver to market the natural gas that accompanies oil production. Similarly, as shale development grew in Pennsylvania, the State adopted a policy that effectively ended the treatment of fracking wastewater at publicly owned treatment plants, which were shown to be poorly equipped to properly treat the water.

Pennsylvania has switched from being a major importer of natural gas to being a major exporter. Acquiring regulatory approval and building the necessary pipelines has taken time, progressing to completion in some places but not others.

In 2017 and 2018, private firms finished two major pipeline projects, the Rover and Nexus pipelines, to take Appalachian gas into Michigan and beyond, with the projects adding nearly 1,000 miles of pipeline and 3.2 billion cubic feet of gas per day of capacity. The first phase of the Rover pipeline was finished in August 2017 and ran from Southeastern Ohio (near the Pennsylvania border) to Northwestern Ohio (near the Michigan border). The second phase was finished in May 2018 and extended the pipeline through Michigan and into Canada. The Nexus pipeline was also completed in 2018 and follows a similar route, eventually connecting with existing pipelines near Detroit.

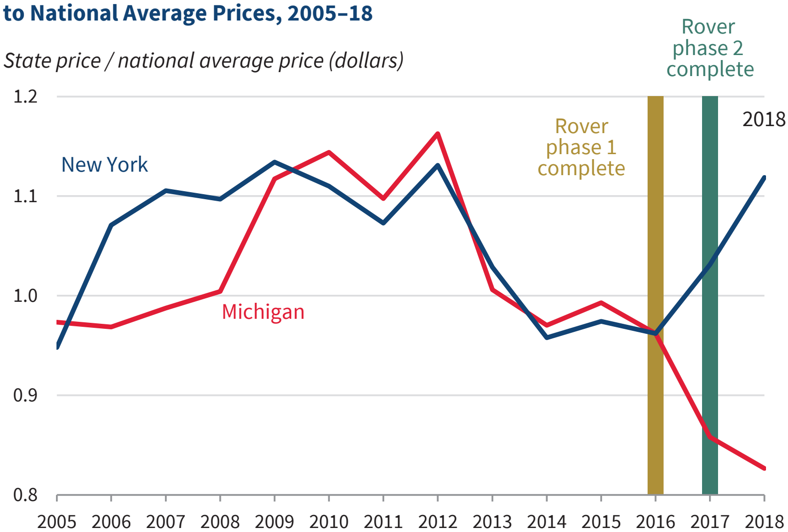
No new interstate pipelines were built from Pennsylvania into New York (and therefore into New England) over the same period. Total expansions or extensions of existing pipelines that transit New York totaled 21 miles in length and 0.46 billion cubic feet per day in additional capacity. The 125-mile Constitution Pipeline, which would take Pennsylvania gas to New York and beyond, has been repeatedly delayed since the project's inception in 2012, with a major source of delay being the refusal of the New York Department of Environmental Conservation to grant a necessary certification.

Natural gas price differences across States and over time illustrate the implications of new investments in pipelines. As natural gas production grew in Pennsylvania, Ohio, and West Virginia, citygate prices in Michigan fell relative to the national average price, plausibly reflecting the benefit of being closer to a place of burgeoning supply growth. (The citygate price measures local wholesale natural gas prices). From 2016 to 2018, when two main pipeline projects were being completed, the Michigan price relative to the national average price fell 14 percent. The New York price went in the opposite direction, increasing by 16 percent, potentially reflecting the interaction between high demand (from an above-average number of cooling-degree days in 2018) and pipeline constraints (figure 4-18).

The 14 percent decline in the Michigan citygate price relative to the national price provides a credible estimate of the price effect of expanded pipeline capacity. It is similar to estimates of the effect of major capacity expansions (Oliver, Mason, and Finnoff 2014) or the price premium associated with insufficient capacity (Avalos, Fitzgerald, and Rucker 2016).

A 14 percent decline in the New York and New England citygate price would save consumers in the region an estimated $2.0 billion annually, or $233 for a family of four. Some of the savings would be from residential, commercial, and industrial consumers paying less for the natural gas that they consume, but the bulk of savings would be from lower electricity prices. New York and most of New England have deregulated electricity markets, where

Figure 4-18. Citygate Natural Gas Prices in Michigan and New York Relative to National Average Prices, 2005–18



Sources: Energy Information Administration; CEA calculations.
Note: The Rover Pipeline phase 1 was completed in August 2017, and phase 2 was completed in May 2018. Vertical bars represent the beginning of the year when the pipeline was completed, given annual data.

electricity-generating firms sell into competitive markets. Linn, Muehlenbachs, and Wang (2014) find that for New York and New England, a 1 percent decrease in the price of natural gas lowers the price of electricity by 0.8 percent. Applying this gas-driven decline in wholesale prices to the region's consumption of electricity in 2018 provides $1.2 billion of the total $2.0 billion in savings.

Other infrastructure investments could provide similar value. The Atlantic Coast Pipeline, for example, would take natural gas from West Virginia to North Carolina, where citygate prices have been about 10 percent higher than in West Virginia in 2019. We also note that pipelines are not the only means of transporting natural gas domestically. The Pipeline and Hazardous Materials Safety Administration recently approved a permit request to transport LNG by rail.

Just as pipelines allow producers to reach high-price markets in other states, facilities for exporting LNG allow U.S. producers–whose production now exceeds domestic consumption–to reach high-price markets abroad. In response, export volumes have surged, averaging 4.7 billion cubic feet per day (Bcf/d) in the first 10 months of 2019, compared with less than 2 Bcf/d in the first 10 months of 2017. Under the Natural Gas Act, exports of LNG must be approved by the DOE on the basis of whether the exports are consistent with the public interest. Under the Trump Administration, the DOE has doubled the volume of LNG approved for export, increasing capacity from 17 Bcf/d to more than 34 Bcf/d as of October 2019.

Conclusion

The shale revolution provides a striking example of the potential of private sector energy innovation and the resulting implications for consumers and the environment. In less than a decade, productivity in oil and gas extraction has increased several-fold. As a result, production costs have fallen, making energy goods and services more affordable for consumers, especially lower-income households. By several measures, the shale revolution has led to greater environmental progress in the United States than in the European Union, which exercises more government control and has more stringent emissions policies.

The Trump Administration's deregulatory policies aim to support private sector innovation and initiative by reducing excessively prescriptive government regulation. In doing so, the Administration seeks to further unleash the country's abundant human and energy resources. This policy stance is consistent with the approach taken by most States, which have allowed shale production to flourish as long as companies meet updated State policies that limit risks to human health and the environment. However, some States have taken a more command-and-control approach, which has had predictable effects. In particular, New York State has taken an alternative, unsafe-at-any-speed approach to shale development. As it has done so, its natural gas production has fallen, its imports of electricity have increased, and its rate of GHG emissions reduction has been less than that of neighboring Pennsylvania.

State and Federal policy questions related to shale will persist in debates about environmental and energy policy. The shale revolution will continue to influence energy prices because the private sector has shown that large amounts of oil and gas can be extracted from shale and similar formations at moderate prices. The knowledge and capability gained from innovation will remain through periods of low energy prices that drive overleveraged firms into bankruptcy. In addition, policies that would severely constrain use of this capability come with large, forgone benefits—in large part the consumer savings and environmental gains documented in this chapter. The Trump Administration's deregulatory energy agenda, in contrast, seeks to overcome government barriers to private sector innovation that lowers energy prices and benefits the environment.