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# Coal Killer

## How Natural Gas Fuels the Clean Energy Revolution

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# Table of Contents

# Executive Summary

The rapid replacement of coal by cheaper and cleaner natural gas has helped drive emissions down in the United States more than in any other country in the world in recent years. Cheap natural gas is crushing domestic demand for coal and is the main reason for the rapid decline in US carbon emissions. The gas revolution offers a way for the United States and other nations to replace coal burning while accelerating the transition to zero-carbon energy.

In the United States, coal-powered electricity went from 50 to 37 percent of the generation mix between 2007 and 2012, with the bulk of it replaced by natural gas. Energy transitions typically take many decades to occur, and the evidence suggests that the natural gas revolution is still in its infancy. The successful combination of new drilling, hydraulic fracturing ("fracking"), and underground mapping technologies to cheaply extract gas from shale and other unconventional rock formations has the potential to be as disruptive as past energy technology revolutions — and as beneficial to humans and our natural environment.

This report reviews the evidence and finds that natural gas is a net environmental benefit at local, regional, national, and global levels. In recent years, the rapid expansion of natural gas production has provoked legitimate local concerns about noise, air, water, and methane pollution that should and can be addressed. But the evidence is strong that natural gas is a coal killer, brings improved air quality and reduced greenhouse gas emissions, and can aid rather obstruct the development and deployment of zero-carbon energies.

The coal-to-gas switch is not inevitable. Concerns about the environmental impacts of natural gas have kept shale fracking out of New York State and resulted in opposition to expanded natural gas production around the country. Gas production levels flattened in response to low prices; more recently, as such unsustainably low prices have risen, coal has regained some of its lost share in the energy mix. American policymakers will make a series of decisions that directly affect the pace of the global and American transition to natural gas. These decisions should be made with an eye to reducing the negative side effects of gas production, increasing production and consumption of gas, and reducing the production and consumption of coal — three goals that are consonant with both improved environmental quality and economic growth.

This report evaluates the key claims and counter-claims made about the environmental impact of natural gas production, and comes to the following conclusions.

1. **The climate benefits of natural gas are real and are significant.** Recent lifecycle assessments studies confirm that natural gas has just half as much global warming potential as coal. The evidence suggests that the lower carbon intensity of natural gas far outweighs the warming caused by today's level of methane leakage. Methane is about 20 times more potent as a greenhouse gas than $CO_2$ on a 100-year basis, and about 70 times more potent on a 20-year basis. Early estimates of methane leakage at levels approaching 7 percent were outliers, and the best estimates of average leakage rates range between 1 and 2 percent. Additionally, methane leakage can be managed and will continue to decline as stricter state regulations enter into force and as the industry moves toward better well completion practices, better compliance with other best practices, and continued technological innovation.

   It is not the case that reduced US coal consumption has been offset by increased exports of US coal. From 2008 to 2012, annual coal consumption for US electric power declined, on average, by 50 million tons. Over the same four years, annual exports increased by only 14.5 million tons on average.

2. **Cheap gas helps rather than undermines the development and deployment of zero-carbon energy sources like solar and wind, and does not significantly add to the challenges facing the nuclear power industry.** The deployment and overall development of many zero-carbon energy sources — including solar, wind, and nuclear — depends primarily on public policies such as mandates and subsidies, not on the price of natural gas.

Rather than being opposed by natural gas, intermittent renewables like solar and wind depend on flexible generation to balance the variability that they introduce into the grid. Natural gas-fired power plants are ideally suited to this task. At present there are few scalable and inexpensive grid-scale storage options, which is why flexible, gas-fired power plants are critical to integrating large volumes of variable solar and wind farms. The corollary to this is that renewables tend not to displace nonvariable base-load sources of energy like coal and nuclear, more often replacing natural gas. If it weren't for natural gas' flexible generation, renewables would have far less value as increasing contributors to the electricity grid.

The nuclear power industry has long faced numerous unique obstacles, including a complex regulatory process, lengthy construction times, high capital costs, frequent cost overruns, and public skepticism. The challenges faced by the nuclear industry, especially the building of new plants, are made marginally more difficult by the ongoing natural gas revolution. However, gas's impacts on nuclear pale in comparison to its impacts on coal, and the long-term imperatives for nuclear power — technological innovation, modularization and standardization of design, and cost reduction — are not changed by the arrival of cheap natural gas.

With much of the world's fossil resources expected to be extracted and burned in the coming decades, experts agree that carbon capture technologies will prove to be an essential component of technological portfolios to mitigate climate change. While carbon capture and sequestration technologies (CCS) are often considered in the context of new and existing coal-fired power, there are reasons to expect that CCS will be more easily developed and deployed with natural gas plants. The cleaner stream of emissions from natural gas combustion and the lower capital costs of gas plants make CCS retrofits and demonstrations attractive options for carbon mitigation.

The claim that new natural gas plants are a "sunk investment" and slow the transition to zero-carbon energy sources is undermined by the low-capital costs of gas electricity. The capital costs of new coal, nuclear, and renewable (wind, solar, geothermal, and biomass) power plants are typically several times greater than those of gas plants.[1] In contrast to these other sources, the greatest cost of natural gas is the fuel, not the equipment. Variable operation and fuel costs can be as much as 70 percent of the total levelized cost of a natural gas power plant. By comparison, variable costs for new coal and nuclear plants are, respectively, only about 30 percent and 10 percent of the total levelized cost.[2]

Finally, the low prices created by the shale gas revolution have generated more than $100 billion in energy cost savings every year since at least 2009,[3] giving strong justification to critical subsidies and R&D investments by the Department of Energy starting in the early 1970s. The unconventional gas boom also generated $31 billion in state and federal revenues in 2012, revenues which are expected to grow to over $55 billion by 2025.[4] By 2015, the additional wealth added to the American economy by the shale gas revolution will alone have exceeded the cost of all federal energy subsidies between 1950 and 2012.[5]

3. **Natural gas production generally and shale fracturing specifically have a far smaller impact on mortality and disease, landscapes, waterways, air pollution, and local communities than coal mining and coal burning.** This is not to say that there are no real hardships experienced by communities and individuals or negative environmental impacts from the expansion of natural gas production. There are, and they should be proactively confronted. But making a normative judgment about energy policy requires asking whether the impacts of gas production are more or less than the impacts of the fuel it is replacing, principally coal.

   The environmental and community impacts of shale fracking are reliably far more modest than those created by coal mining and production. Whereas coal mining removes entire mountains and contaminates streams with hazardous waste, natural gas drill pads occupy only a few hundred square feet, and there are only a handful of cases of groundwater contamination by fracking chemicals. Whereas innovation in coal mining resulted in greater landscape degradation, innovation in gas fracking has resulted in less-toxic fracking chemicals, fewer drill pads, and better drilling practices.

Accelerating the shift from coal to natural gas should be one of the highest energy policy priorities of policymakers and the public. The revolution in shale fracturing and mapping technologies opens up the possibility for developed and developing countries alike to radically reduce consumption of coal in ways that accelerate rather than slow economic growth. Natural gas that is cheaper than coal makes it easier for the Environmental Protection Agency to impose more-stringent air pollution regulations on coal power plants. And cheap natural gas boosts higher rates of economic growth and national wealth to invest in developing its eventual zero-carbon replacements.

## Recommendations:

1. **Accelerate the coal-to-gas shift in the United States.** Better state regulations and industry oversight should be encouraged to continuously improve the environmental performance of gas drilling, and to address public concerns about pollution and noise. Such efforts will help lay the groundwork for expanded natural gas production on public and private lands. Policymakers should also support the export of liquefied natural gas, which will provide greater price stability, helping the industry avoid the boom-bust cycle that stalled gas production in 2012. Policymakers should also consider including natural gas in any future clean energy standards.

2. **Reduce coal consumption and coal exports.** The Obama administration should pursue stronger pollution and carbon dioxide regulations to make coal increasingly expensive and incentivize the switch to natural gas. Policymakers should support policies that would leave US coal in the ground, rather than mining it for export to Europe and Asia. There will be no net environmental benefit if all of the coal that the US was going to burn for its domestic electricity is exported abroad. US policymakers could reduce global coal supplies and encourage gas production by restricting and eventually halting all US coal exports.

3. **Export natural gas technologies to coal-dependent countries.** The US and global development institutions should promote gas exploration in other countries in ways that accelerate economic development and improve local environmental quality. Such an effort would align United Nations energy access goals with US and international climate goals. It would help China, India, South Africa, and other developing nations to reduce air pollution and meet growing energy demand. And it would help diversify the number of energy exporters around the globe, reducing some of the geopolitical risks associated with geographically disproportionate energy reserves.

4. **Pay it forward.** The shale gas revolution has contributed more than $100 billion to the economy every year since 2009 in the form of lower energy prices. Within five years the economic benefits from shale gas alone will pay for all US energy subsidies since 1950. The critical role that US subsidies played in enabling the shale gas revolution, and its extraordinary economic benefits, suggests that policymakers should make long-term investments in innovation of renewables and nuclear energy. The rapid gas revolution in the United States demonstrates the effects of sustained public-private technology investments, providing a model of a successful energy transition for zero-carbon options like renewables and nuclear.

# I. Introduction

The global consumption of coal for industrial power and electricity quickened in the first decade of the 21st century, reversing the 200-year-long process of energy decarbonization.[6] Much of the new coal demand is coming from the developing countries in Asia, with China adding the equivalent of two 500-megawatt coal power plants per week[7] and India at a rate of about one every two weeks.[8] But even wealthy countries have tilted back toward coal. As it has recovered from recession, Europe has increased its coal consumption each year since 2009.[9] Fossil fuel-fired electricity in Germany rose 9 percent in 2012, driven by an increase in coal. In 2013, Germany is expected to bring 5.3 gigawatts of new coal-fired electric capacity online, which alone will generate an amount of electricity roughly equivalent to the nation's total installed solar capacity.[10] By 2017, coal may rival petroleum as the world's largest primary energy source.[11]

The rapid growth of coal consumption has led climate scientists and environmentalists concerned about global warming to seek its replacement. "Coal is the single greatest threat to civilization and all life on our planet," then-National Aeronautics and Space Administration climate scientist James Hansen said in 2009, and referred to trains carrying coal as "death trains."[12] Former Vice President Al Gore called for civil disobedience against coal plants in the United States.[13] And New York Mayor Michael Bloomberg contributed $50 million in 2011 to the Sierra Club's "Beyond Coal" campaign,[14] which aims to accelerate coal plant closings.

Emissions from coal plants cause more than 20,000 heart attacks, nearly 10,000 hospitalizations, and more than 13,000 premature deaths annually in the United States.[15] In 2008 the World Health Organization estimated that coal particulates pollution causes approximately one million deaths each year around the world,[16] or about a third of all premature deaths related to air pollution. Coal combustion releases toxic chemicals including arsenic, mercury, lead, and numerous others. In addition to $CO_2$, coal combustion also emits oxides of sulfur (mainly $SO_2$), and oxides of nitrogen ($NO_x$), which can cause adverse respiratory conditions. Hydrogen cyanide (HCN), sulfur nitrate ($SNO_3$), and other toxic substances are also produced. $SO_2$ reacts with atmospheric gases to produce sulfuric acid, which returns to the earth as acid rain, harming ecosystems and human health.

Coal mining dramatically degrades landscapes. Mountaintop removal obliterates natural landscapes, destroys wildlife habitat, and creates serious downstream impacts and human health dangers. Underground mining results in waste materials being piled at the surface of the mine, creating runoff that pollutes and alters the flow of regional streams. Explosive blasting in mines causes groundwater to seep to lower-than-normal depths, contaminating aquifers. Studies have shown that rates of adult hospitalization for chronic pulmonary disorders, hypertension, and lung cancer, as well as mortality rates, are elevated as a function of county-level coal production.[17]

Environmental experts and advocates have long viewed natural gas as a critical driver of the shift from coal toward lower-carbon energy sources. Widely referred to as a "bridge fuel," natural gas proponents argue it is one of the lowest-cost and most easily substitutable alternatives to coal. Because it produces roughly half the $CO_2$ emissions of coal, natural gas has been embraced as a bridge fuel to zero-carbon energy supplies by Al Gore,[18] the Sierra Club,[19] the Natural Resources Defense Council (NRDC),[20] Resources for the Future,[21] former Environmental Protection Agency head and Obama climate chief Carol Browner,[22] and energy experts across the political spectrum.[23]

But the expansion of natural gas production in recent years has triggered concerns that have led policymakers, climate scientists, environmentalists, and members of the public to question prior support for natural gas as an environmental improvement over coal. The first concern is that fracking's effects on landscapes, waterways, and communities are as bad as coal mining. Second, the leakage of uncombusted natural gas, or methane, a potent greenhouse gas, cancels out the carbon benefit. Third, natural gas undermines rather than supports the transition to zero-carbon energy sources including solar, wind, and nuclear. The fourth concern is that even if natural gas manages to displace coal, the overall $CO_2$ emissions reductions associated with that displacement are not sufficient to stabilize atmospheric $CO_2$ at noncatastrophic levels.

These concerns have led many US environmental groups and environmentally concerned Americans to oppose the expansion of natural gas production and consumption, even to replace coal. Rather than promoting the safe and productive natural gas exploration, both the NRDC and the Environmental Defense Fund (EDF) appear focused on limiting natural gas production.[24, 25] EDF President Fred Krupp has publicly stated his opposition to expanded natural gas production.[26] The Sierra Club,[27] 350.org, Greenpeace,[28] and other organizations actively oppose natural gas production, and environmentally concerned celebrities including Yoko Ono, Scarlett Johansson, Mark Ruffulo, and Matt Damon have run advertisements and urged a halt to natural gas production.[29]

This report reviews the available evidence and concludes that replacing coal with natural gas remains a net environmental positive at the local, regional, national, and global levels. Moreover, the claim that cheap natural gas undermines the development and deployment of zero-carbon alternatives like renewables and nuclear is not supported by the evidence, which suggests that cheap natural gas can instead accelerate the transition to zero-carbon energy sources. Natural gas remains a disruptive technology and a critical bridge to a zero-carbon energy sector.

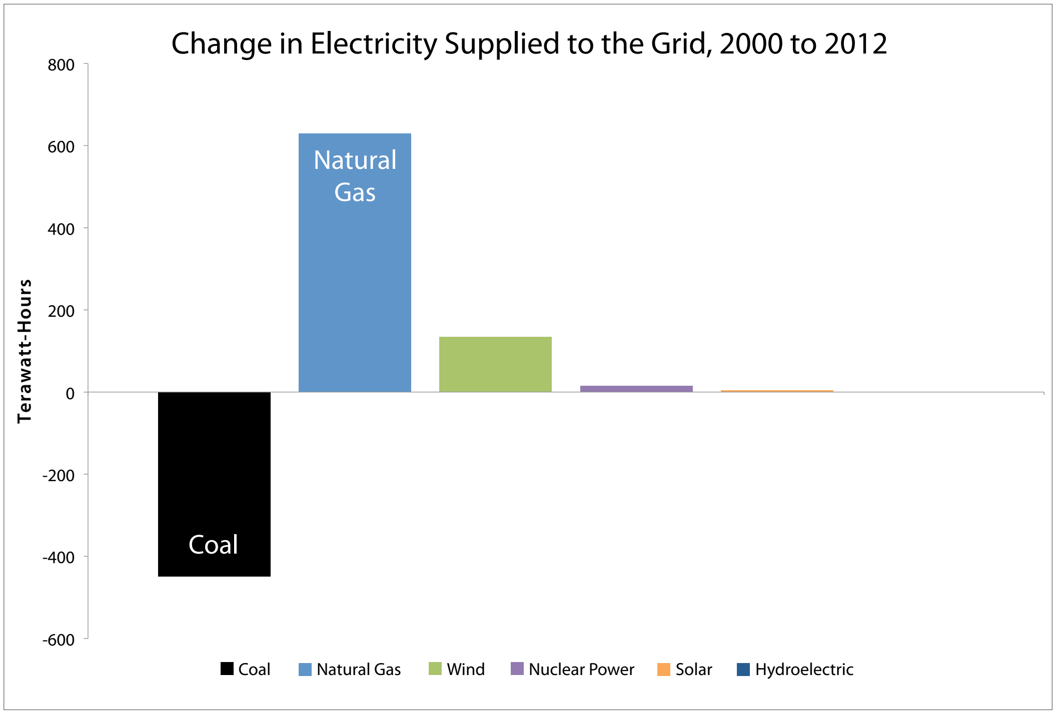
Nevertheless, the transition to natural gas, as with all energy transitions, is not guaranteed. Technology and policy choices by governments and civil society will prove critical in guiding the United States and the world's transitions away from coal toward lower-carbon energy sources. In the United States, coal-fired power has already begun to eat back some of its recent losses as natural gas prices rise from current unsustainable lows.[30] In this report, we recommend a set of policy actions to accelerate the shift from coal to cleaner natural gas, to export the gas revolution to other countries, and to pay forward the benefits of the gas revolution to sustain technological innovation in zero-carbon energy technologies.

# II. Natural Gas is a Net Climate Positive

## A. The Transition from Coal to Gas

While the world as a whole is turning to coal, the United States is moving away from it. Coal's share of electricity has declined by 11 percentage points in the US in the past five years, from 48.5 percent in 2007 to 37.4 in 2012.[31] The US has only been able to reduce coal consumption because of the availability of a low-cost, technologically ready substitute, natural gas.[32] Over the past 10 years, more than 160 coal plant proposals have been cancelled — 50 gigawatts of coal capacity have been retired since January 2010 alone.[33, 34] Since 2000, coal-fired generation has declined by an average of nearly 40 terawatt-hours (TWh) each year, while gas has increased by an average of more than 50 TWh each year.

Figure 1



Predictions of future natural gas consumption and price levels are famous for being more often wrong than right, but it is likely that the long-term trend away from coal to gas will continue. The Energy Information Administration (EIA) projects that between now and 2020 some 50 gigawatts (GW) of aging coal capacity will be retired — about a sixth of existing coal capacity in the United States — as a result of lower natural gas prices, higher coal prices, slower economic growth, and new EPA regulations.[35] The North American Electric Reliability Corporation (NERC) projects that more than 71 GW of fossil fuel capacity — the majority coal — will be shuttered by 2022.[36] The International Energy Agency states that under the right policy support for shale gas development, natural gas could comprise 25 percent of the world's primary energy supply by 2035 — compared to 21 percent in 2010.[37]

The EIA projects that by 2020 coal power generation will supply 39 percent of the nation's electricity — down from over 48.5 percent in 2007 — while natural gas and renewables (including conventional hydroelectric) will supply 26 percent and 14 percent, respectively.[38] Under that scenario, by 2020 the nation's power sector will emit 500 Mt less $CO_2$ annually than it would if the carbon intensity had remained fixed at 2007 levels.[39] A 2011 modeling analysis from researchers at the Massachusetts Institute of Technology projected that the nation could reduce power-sector carbon emissions by 20 percent simply by increasing the utilization of existing natural gas capacity.[40]

While a small number of analysts[41] were too early in predicting the natural gas revolution, the EIA has, in the past, mostly underestimated it. In 1998, EIA predicted gas production would rise from 19 trillion cubic feet (Tcf) in 1996 to 27 Tcf in 2020.[42] In 2000, EIA revised those estimates upward to 29 Tcf. But production had already reached 28.5 Tcf by 2011. This experience suggests great caution is merited in predicting natural gas production and consumption levels even one decade hence.

The past several years saw a dramatic increase in identified "proven reserves" of natural gas, those reserves where there is a high degree of certainty that gas will be commercially recoverable. In 2013, proven gas reserves rose to the highest amounts ever recorded since the EIA began publishing estimates in 1977.[43] The most important factor has been the nationwide expansion of horizontal drilling and hydraulic fracturing in shale and other “tight” formations. The EIA’s most recent calculation of technically recoverable shale resources is 13 percent larger than its 2012 estimate.

Some analysts have expressed skepticism about the extent of recoverable shale gas reserves in the United States, claiming that government agencies, analysts, and industry groups have vastly overstated them. They have pointed to overoptimistic assumptions based on limited drilling and production data,[44] unrealistic well production expectations,[45] deliberate industry exaggeration of estimates,[46] and uncertainty in estimates of unproven reserves.[47]

Skepticism has been fueled by dramatic changes in federal estimates of technically recoverable domestic reserves. In January 2012, the EIA released an estimate that the country had 482 Tcf of domestic technically recoverable shale gas reserves, a drastic downward revision (by more than 40 percent) from its 2011 estimate of 827 Tcf recoverable reserves.[48] The decline largely reflects a decrease in the estimate for the Marcellus shale region, from 410 Tcf (2011) to 141 Tcf (2012), a 66 percent drop.

Figure 2

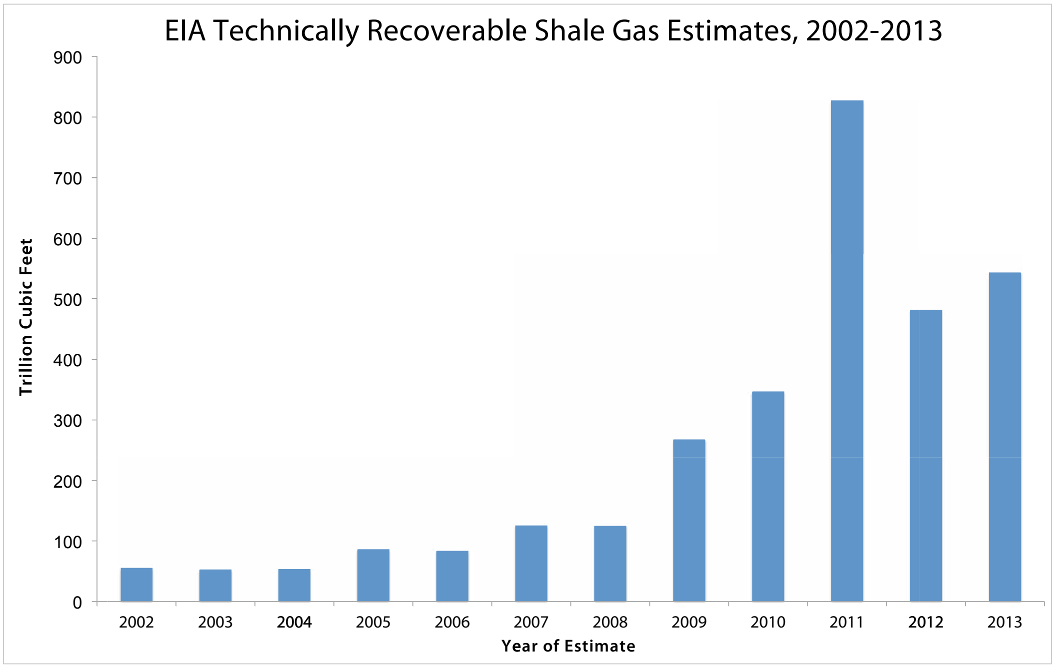
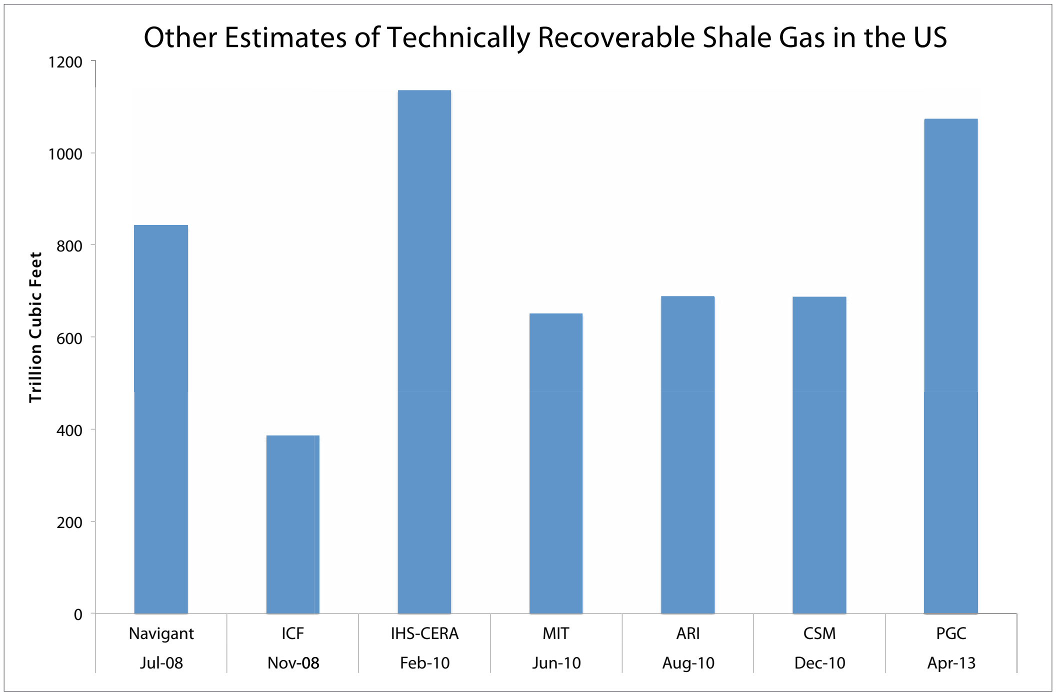


Figure 3

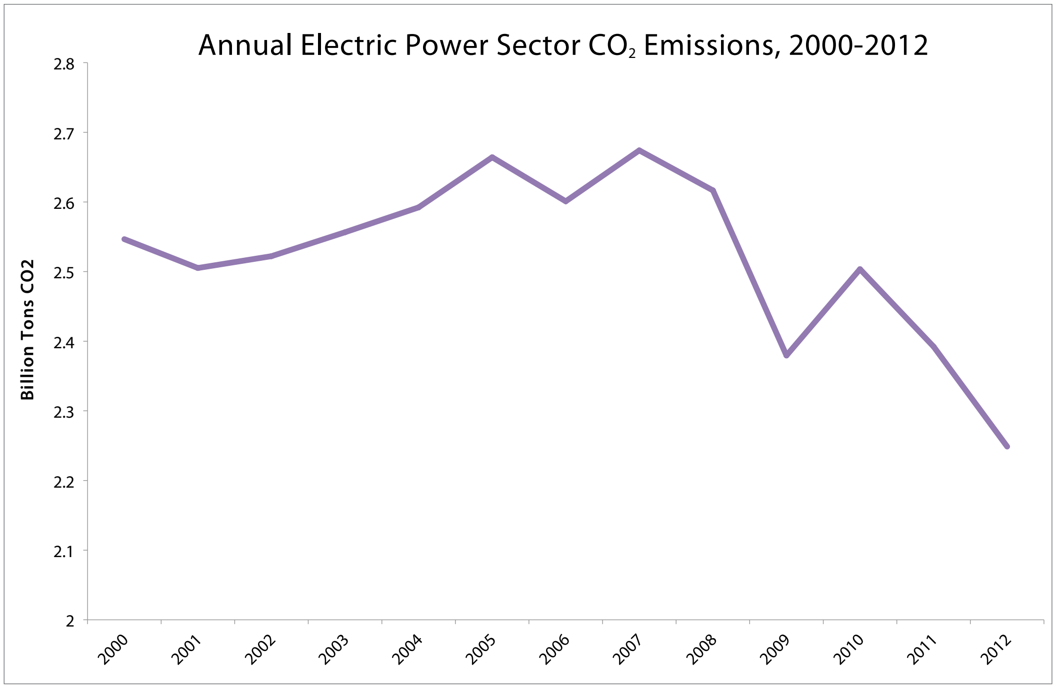


One reason for confidence in newer EIA estimates is that the the United States Geological Survey (USGS) derived them from a large body of new drilling and production data (drilling in the Marcellus region accelerated rapidly in 2010 and 2011).[49] And EIA's numbers are similar to those of the 2010 interdisciplinary Massachusetts Institute of Technology Energy Initiative study, which estimated the nation's technically recoverable reserves at 650 Tcf.[50]

## B. Carbon Emissions Reductions Driven by the Coal-to-Gas Transition

Primarily as a result of the shift from coal to gas, energy-related carbon emissions have declined more in the US than in any other country in the world in recent years,[51] from 6.6 billion tons in 2007 to 5.9 billion tons in 2012. The Department of Energy and EIA project that total 2020 energy-related $CO_2$ emissions will be 9 percent lower than 2005 emissions.[52, 53] In the electric power sector, where most of the country's coal is used, emissions declined from 2.7 billion tons in 2007 to 2.2 billion tons in 2012. In 2012 there were 726,000 fewer train car loads of coal than there were in 2011.[54]

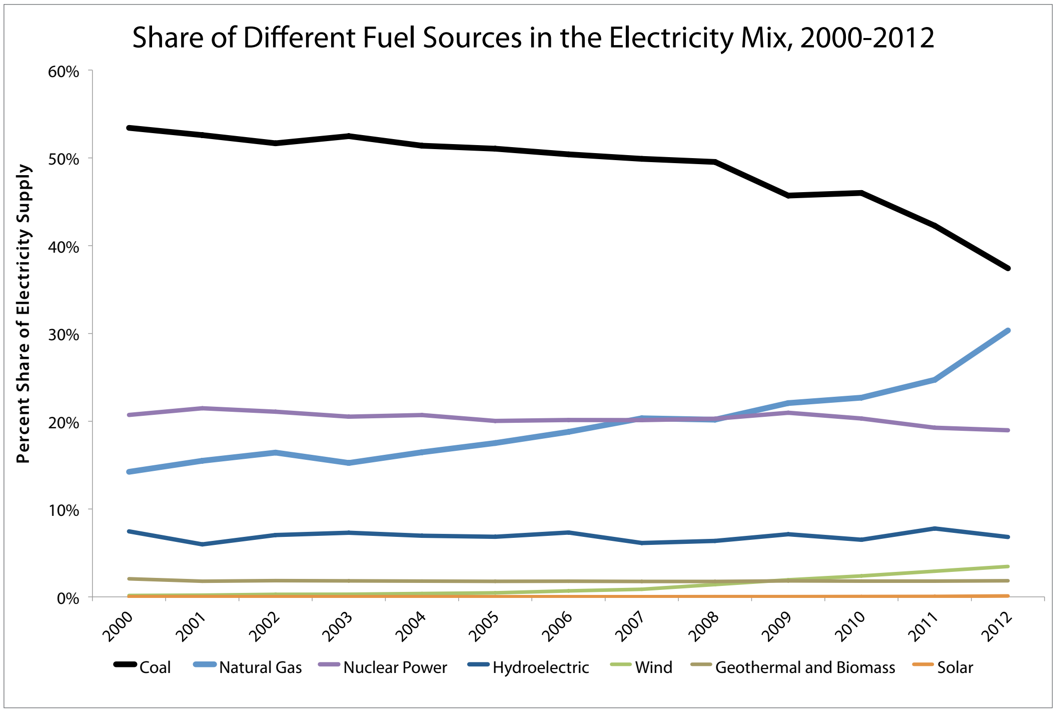
Figure 4



Gas deserves most of the credit for declining US emissions. Experts like the University of California-San Diego's David Victor and others at the National Renewable Energy Laboratory estimate that the shale gas revolution has reduced US emissions between 300 to 500 million tons (Mt) of $CO_2$ per year, about the same amount of total annual $CO_2$ emissions in Australia, Brazil, France, or Spain.[55, 56] John Hanger, former Secretary of the Pennsylvania Department of Environmental Protection, estimates that 77 percent of the $CO_2$ reduction between 2011 and 2012 is attributable to the switch from coal to gas.[57] Council on Foreign Relations energy analyst Michael Levi put half the decrease in carbon dioxide emissions from January-May 2011 and January-May 2012 to the switch from coal to natural gas.[58] The White House Council of Economic Advisors attributes 40 percent of the 2005-2012 emissions reduction to "fuel switching to natural gas and renewables,"[59] and energy analyst John Miller estimates that the coal-to-gas switch is the largest single factor for emissions reductions over the same time period.[60]

We estimate that $CO_2$ emissions reductions resulting from the coal-to-gas switch in the past several years have been 3-10 times greater than for non-hydro renewables. The share of natural gas in the electricity supply mix increased by 10 percentage points between 2007 and 2012, from 20.3 percent to 30.4 percent. Over the same period, the share of non-hydro renewable supplied to the electric power sector only increased by 2.6 percentage points, from 0.9 percent in 2007 to 3.5 percent in 2012.[61] In 2012, natural gas electricity generation increased by about 10 times more than the increase in wind generation, relative to 2011, and about 100 times more than the increase in solar generation.

Figure 5



It is unlikely that wind and solar will contribute significantly to the decarbonization of the electricity sector in the next decade, despite the fact that they're poised to supply increasing amounts of power to the grid. For wind and solar to be effectively integrated into the grid, they rely on additional backup and spinning reserve capacity. Historically, intermittent renewables have supplemented, not displaced, fossil fuels,[62] and wind and solar today displace marginal gas generation far more than they displace coal.[63] While we should expect non-hydro renewables' role in reducing emissions to increase in the short- to medium-term, this will occur in partnership with expanded and newly utilized flexible gas capacity.[64]

The extent to which renewables do displace fossil fuel generation and lead to $CO_2$ emissions reductions depends crucially on the types of electricity generation (coal, gas, nuclear, hydro, etc.) in a given region. A recent analysis by researchers at the Colorado School of Mines, for example, finds that in coal-dominated regions wind power may save 0.9 tons of $CO_2$ for each megawatt hour (MWh) of wind power generation, while coal generation typically releases closer to 1.1 tons of $CO_2$ per MWh. In other regions, where renewables replace more gas than coal, the researchers find that savings could be as low as 0.3 tons $CO_2$ per MWh (see Figure 6 for regional displacement factors from wind power).[65] While aggregate estimates of $CO_2$ displacement by renewable power are unavailable, it is clear that their deployment will not match the emissions reductions of coal-to-gas switching in the near- to medium-term. Even as renewables impact on emissions increases, their ability to displace coal will likely remain limited for the foreseeable future.

Figure 6

| Region | Emissions Displacement from Wind Power ($tCO_2$/MWh) |
|---|---|
| BPA (Pacific Northwest) | 0.08 |
| CAISO (California) | 0.29 |
| PSCO (Colorado) | 0.40 |
| ERCOT (Texas) | 0.52 |
| MISO (Midwest) | 0.92 |

In spite of the well-established carbon emissions benefits associated with switching from coal to gas, the long-term climate benefits of the coal-to-gas switch have been called into question due to both concerns about fugitive methane emissions from shale gas production and the fact that switching from coal to gas reduces $CO_2$ emissions but does not eliminate them.

## C. Methane Leakage

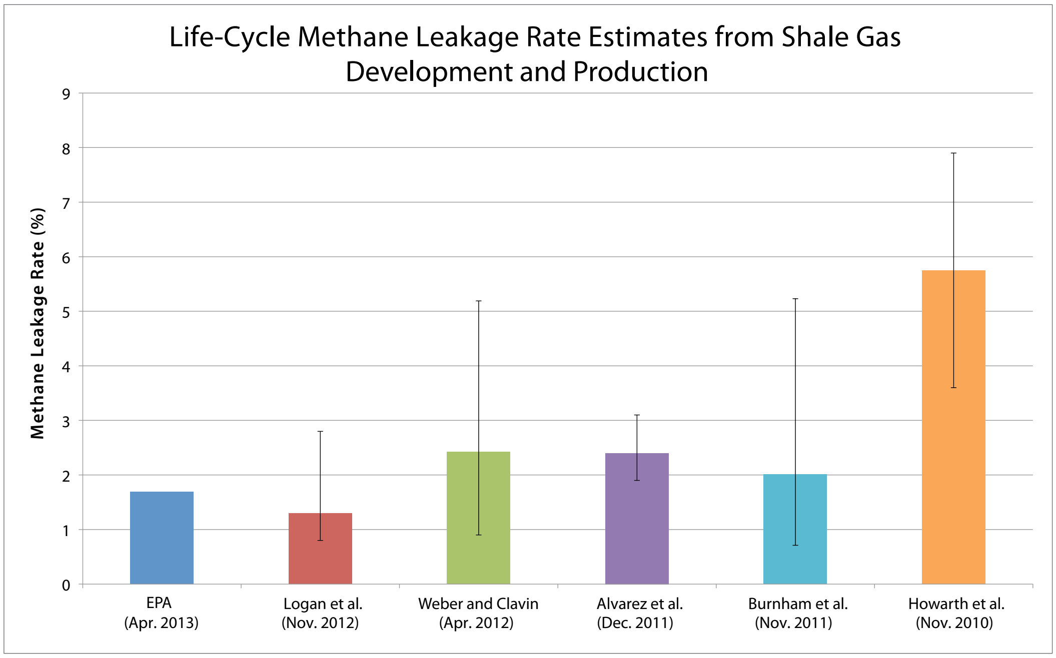
Methane is about 20 times more potent as a warmer than $CO_2$ on a 100-year basis, and about 70 times more potent on a 20-year basis. A small fraction of the methane contained in natural gas escapes to the atmosphere during the “drill-out” and “flow-back” phases of a shale gas well’s production lifetime. Fugitive emissions may also occur during the well construction, transport, and consumption of natural gas. As a result, methane emissions over the short term have the potential to erode most or all of the $CO_2$ emissions benefit resulting from switching from coal to gas.

### i. Estimates of methane leakage vary

There is a high degree of uncertainty regarding methane leakage rates. Estimates of fugitive emissions vary, ranging from 1 percent to 7 percent of total production.[66, 67, 68] Several early studies contained very high estimates of methane emissions from unconventional gas production. One 2011 paper finds fugitive methane emissions to be 3.6 to 7.9 percent,[69] while a 2012 study by scientists at the National Oceanic and Atmospheric Administration reported a 9 percent leakage rate in Colorado. However both studies appear to be outliers and have been widely faulted for selective bias and poor measurement and statistical techniques.[70, 71]

Most recent publications indicate a leakage rate of 1 to 2 percent.[72, 73] Using a tested methodology, our own calculations show that the 6,646 gigagrams of methane that were accounted for by the EPA in 2011 amount to less than 1.5 percent of total natural gas production.[74] Another study published by the Joint Institute for Strategic Energy Analysis estimates leakage at 1.3 percent.[75]

Figure 7



However, there is broad agreement that data on fugitive methane can and should be made more robust. A number of major new studies of leakage rates will be forthcoming over the next year and should provide a more accurate estimate of industry-wide leakage rates.

Nonetheless, it is already clear that leakage rates could, and probably will, be lowered substantially in the future. One study found that 70 percent of total leakage was occurring in only 10 percent of wells, suggesting that the problem is not evenly distributed and the potential for low-cost, high-impact interventions is significant.[76]

Public concern about leakage has already led to stronger government regulation as well as efforts by the gas industry, in partnership with environmental groups, to increase the use of best practices.[77] Moreover, because methane has a high economic value, there are strong financial incentives to reduce leakage.[78] An MIT analysis of

4,000 horizontal wells that were brought online in 2010 found that in most cases, capturing methane emissions was profitable to drillers.[79]

A recent report from the World Resources Institute identifies several promising options for further limiting fugitive methane emissions, including monitoring and repair systems, more-efficient pneumatic devices that capture fugitive emissions, and plunger lift systems to remove excess fluid in wells without venting excessive amounts of methane.[80] The authors of the report expect that these opportunities will be attractive to most drillers, and that implementation of these simple measures can keep methane leakage to reasonable levels. Steps in the direction of more-aggressive methane capture are already being taken. According to a senior scientist from the Environmental Defense Fund, over 90 percent of wells use “green completion” techniques to seriously reduce fugitive emissions, where only a quarter of wells used these techniques as recently as two to three years ago.[81]

### ii. Methane leakage has little impact on long-term warming

Methane leakage rates, however, appear to have little impact on long-term warming trends, according to climate models assuming different leak levels over the century-scale timeframe that matters most in the context of global warming. Studies that use high leakage rates find that a long-term, permanent shift from coal to gas would have little impact on long-term warming,[82, 83] yet studies that assume no methane leakage arrive at similar conclusions.[84]

Climate modeling suggests that the implications of a long-term global shift from coal to gas are largely determined by assumptions about the thermal efficiency of future coal plants and whether the switch to gas is permanent or a bridge to zero-carbon energy sources in the middle and latter portions of the 21st century.

Studies that assume that future coal plants will be significantly more efficient than present-day plants, and that the switch to gas is permanent and not a bridge, find little climate benefit from the switch to gas. Studies that are more pessimistic about the future efficiency of coal plants or that assume that gas serves as a bridge to zero-carbon energy sources find that switching to gas today brings significant climate benefits.[85, 86]

For a variety of reasons, regulatory and technological efforts to reduce methane leakage make sense. The long-term climate benefits of the coal-to-gas switch, however, will largely be determined by how quickly zero-carbon technologies are able to displace gas. For the next several decades, natural gas offers a sizable emissions-reduction benefit over coal, while other low-carbon technologies mature. The long-term climate benefits of the coal-to-gas switch will depend upon how rapidly those technologies mature and the degree to which the gas revolution impedes or assists that maturation process.

## D. Natural Gas as a Bridge to a Zero-Carbon Future

Most scenarios that project long-term coal-to-gas switching do not model gas as a bridge fuel (i.e., an eventual phase-out of gas and phase-in of other zero-carbon energy sources).[87, 88, 89] These scenarios lead to low, modest, or no climate benefit compared to a baseline, coal-dominated future.

One of the only studies that does model natural gas as a bridge fuel finds that it could play a significant role in limiting the atmospheric $CO_2$ concentration to 550 ppm, and less of a role in limiting the concentration to 450 ppm.[90] This finding should not be a surprise. Limiting global temperature increase to under two degrees Celsius and global atmospheric $CO_2$ concentrations to below 450 parts per million would require that we stop building new fossil fuel infrastructure in the next several years and significantly reduce energy demand over the next few decades. Achieving these outcomes is highly unlikely due to rapid energy demand growth in China, India, and other non-OECD countries, and carbon emission “lock-in” from existing fossil fuel infrastructure. In its most recent 450-ppm stabilization scenario, for instance, the International Energy

Agency notes that four-fifths of the $CO_2$ emissions allowable by 2035 are already locked in by energy infrastructure, and that if significant action to reduce $CO_2$ emissions is not taken before 2017 it will be impossible to avoid 450 ppm.[91]

Although limiting global atmospheric $CO_2$ concentration to 450 parts per million is probably unachievable, our focus should remain on reducing emissions as quickly as possible and stabilizing atmospheric $CO_2$ concentration at as low a level as possible. Natural gas has an important role to play in accomplishing this goal, as a bridge to lower-carbon technologies. Even taking fugitive methane emissions into account, it is clear that natural gas offers a sizable emissions reduction benefit over coal for the next several decades. While other low-carbon technologies mature — including renewables, advanced nuclear, and carbon capture — natural gas provides a cheap and abundant source of energy that can mitigate global warming emissions and toxic terrestrial pollution.

In the ongoing process of energy transitions and global decarbonization, the displacement of dirty coal by cleaner natural gas buys time to develop and deploy zero-carbon technologies. As long as abundant, energy-dense fuels like coal and natural gas exist, human societies will extract them — unless better, cheaper, cleaner alternatives arrive to enable their regulation and replacement. Given the strong physical and moral imperatives to provide clean, cheap, abundant energy while reducing carbon emissions as quickly as possible, the time bought by cheap natural gas will prove valuable.

# III. Natural Gas is Fueling the Transition to Zero-Carbon Energy

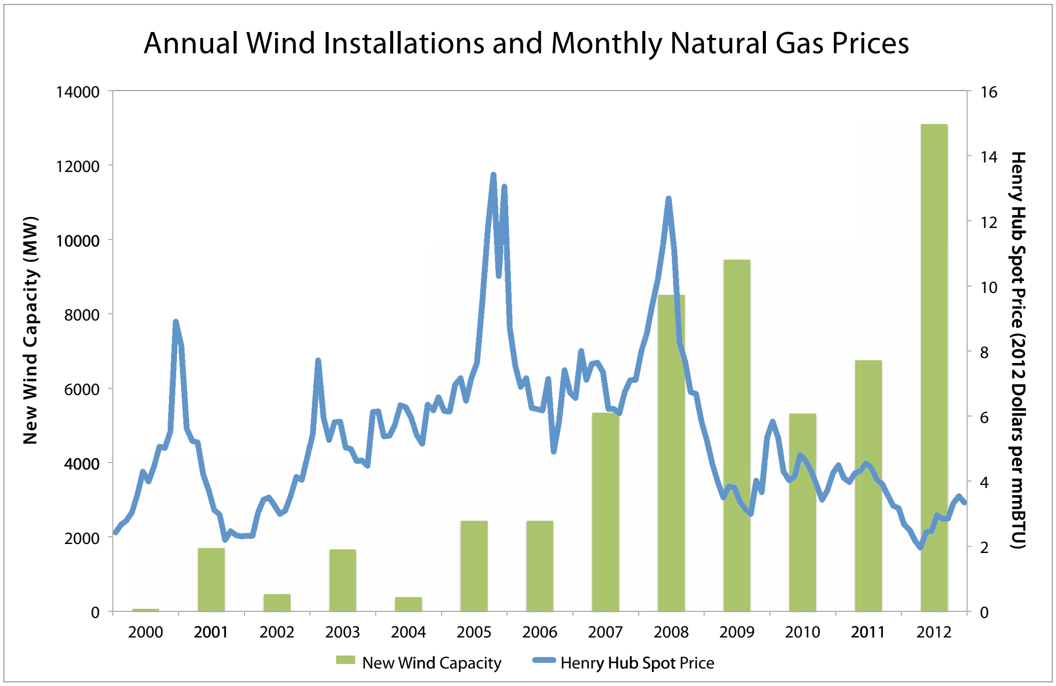
The US shale boom is the clearest contemporary example of the potential for clean, cheap energy to simultaneously accelerate decarbonization, innovation, and the evolution of energy systems. As the world moves toward abundant, cheap, zero-carbon energy, policymakers should not only look to the history of US federal investments in shale fracking as a model for innovation, but should also note the catalytic role that natural gas can play in the development of other clean energy technologies.

Natural gas today is cheaper than both new renewables and new nuclear technologies, a reality that has triggered fears among advocates of both that cheap gas could be an impediment rather than a catalyst to the development and deployment of zero-carbon energy. But there is strong reason to believe that the US gas revolution can strengthen, rather than strangle, efforts to develop zero-carbon technologies like renewables, nuclear, and carbon capture.

The evidence reviewed here confirms that fears of gas “crowding out” other low-carbon technologies are largely misplaced. There is no correlation between wind deployment and natural gas prices (see Figure 8). Rather than being undermined by shale gas, intermittent renewables like solar and wind have benefited from it as an inexpensive source of backup power. While low natural gas prices have added marginally to the challenges faced by the nuclear industry, they have not significantly altered the trajectory of nuclear power, which is faced with a number of unique historical challenges. With lower capital costs and a cleaner stream of power-plant emissions than coal, natural gas also offers a potential development and demonstration platform for nascent carbon-capture technologies. And cheap natural gas, which has added $100 billion annually to the US economy since 2007 in the form of lower electricity prices, creates the national wealth required to continue investing in ever-cleaner and ever-cheaper energy sources.

It is public policies, not fossil energy prices, that overwhelmingly determine whether zero-carbon energy sources get deployed or not. Renewables deployment is dependent on public subsidies and state utility mandates; new nuclear deployment is dependent on loan guarantees, ratepayer tariffs, and innovation funding. Recent wind deployment trends are proof of the industry's subsidy dependence. In 2012, uncertainty over whether Congress would renew the key wind subsidy led to a rush of wind installations, the largest in US history. It is predicted that less than half as much new wind will be installed in 2013 as was installed in 2012.

Figure 8



Acknowledging the obstacles to deployment and subsidy dependence of new renewables and new nuclear is not an argument against those technologies. It took 35 years of public subsidies and policy interventions for shale gas to become a market game-changer. The shale history also shows that the goal is not permanent subsidization, but rather innovation that results in revolutionary new technologies capable of replacing dirtier, more expensive incumbents. The move away from whale oil to camphene and eventually to kerosene was supported by federal government subsidies. Electrification, which came to replace kerosene, was enabled by the federal government. In both cases, subsidies were involved until the technology was able to compete in the marketplace.

We should consider the transition to gas as part of a longer-term transition to nuclear power, renewables, carbon capture, and other low-carbon energy technologies. While it may seem improbable that zero-carbon energy will ever be cheaper or more scalable than natural gas, recall that only a few years ago many energy analysts considered coal unbeatable (in cost) by clean energy. In recent years, natural gas — much cleaner than coal — has done exactly that. How quickly energy transitions occur depends principally on how well innovation policy is enacted.

Energy transitions are not perfectly sequential. Deployment of renewables and nuclear power can occur alongside the transition from coal to natural gas. Indeed, cost-effectively managing renewable intermittency is enabled by cheap backup gas-fired electricity. Natural gas prices have historically fluctuated, and they will continue to do so. Nuclear and renewables provide an important hedge against volatile gas prices.[92]

## A. Cheap Gas Supports Scaling Up of Renewables

Gas-fired power provides cheap, low-carbon, and flexible backup support for intermittent wind and solar. Grid operators depend on reliable power production from power plant operators to match grid supply and demand and ensure consistent price signals. As intermittent renewables — particularly wind — continue to occupy a greater share of the nation's electricity output, power system operators will need to increasingly rely on capacities of backup and firming power. Natural gas-fired power plants offer the best currently available solution.

By contrast, the majority of coal plants in the United States were designed to provide steady baseload power to the grid, with very little flexibility. Today's coal plants have low ramping rates (1.5 percent to 3 percent per minute) and become inefficient if they are operated below maximum output, increasing marginal emissions of $CO_2$, NOx, and $SO_2$ pollutants.[93] Conventional nuclear power cannot be counted on for flexible power in any context today, given extreme technical difficulties in cycling and ramping nuclear generators. Although grid-scale energy storage options are expanding, the technology is still limited in its commercial applicability.

Natural gas power — and particularly power from natural gas combined cycle (NGCC) plants — provides a readily substitutable alternative to baseload and older load-following coal plants.

Flexible gas plants provide support for electric power grids that are increasingly occupied by intermittent wind and solar. A study from researchers at Carnegie Mellon University suggests that for every 4 MW of wind capacity, 3 MW of NGCC capacity will be needed to operate the grid reliably.[94] The expansion of gas-fired power plants could accelerate the integration of intermittent power into existing grid systems.[95] New natural gas plants have ramping rates of approximately 8 percent per minute and can reduce their output to 80 percent capacity with minimal heat rate penalty. New NGCC plants that are specifically designed to offer flexibility to a renewables-heavy grid system can ramp to 150 MW in 10 minutes and to full load in 30 minutes.[96] General Electric's new fleet of gas-fired power plants is designed to optimize integration with variable power sources and can ramp as fast as 100 MW per minute.[97]

Modeling efforts at the National Renewable Energy Laboratory (NREL) find that "large quantities of variable renewable energy and flexible gas generation work synergistically to maintain system reliability requirements."[98] As another analysis from researchers at NREL and the Joint Institute for Strategic Energy Analysis (JISEA) found:

> Natural gas and renewable energy technologies enjoy many complementarities spanning economic, technical, environmental, and political considerations. These complementarities arise from their similarities — which include improved environmental performance compared to coal and oil and their ability to contribute to a robust US economy — but it is from their dissimilarities that the biggest opportunities for mutually beneficial collaboration can be found.[99]

Wind and solar have seen rapid growth in recent years thanks to various subsidies, from federal tax incentives to state mandates. In many jurisdictions, renewable portfolio standard (RPS) mandates require grid operators to utilize renewable generation on a first-priority basis; unlike most other energy sources, wind and solar are protected from the bidding process and are automatically dispatched. While there may be cases where cheap natural gas has challenged the economics of renewable power, the far bigger threat to renewables is subsidy dependence and regulatory uncertainty.[100]

Annual wind installations dipped in 2000, 2002, and 2004 following the expiration of a crucial subsidy, the Production Tax Credit for wind. Yet when protected by the federal tax credit and state RPS policies, wind installations remained unaffected even with low natural gas prices (for example, in 2009) . As portrayed in Figure 8, 2012 saw new records in low natural gas prices as well as annual wind power installation.

The introduction of intermittent renewables complicates the traditional operation of power systems.[101] Utility-scale wind generation, a particularly volatile intermittent power source, requires system operators to make significant adjustments to balance generation and load by issuing instructions for generation plants to increase their output (ramping) or to shut down (cycling).[102] This creates inefficiency in the system because it forces traditional power plants to operate at reduced output, and can erode some of the systems cost savings delivered by zero-fuel-cost renewables generation. [103]

In rare and extreme cases, a rapid influx of intermittent renewable electricity to an ill-prepared grid system can lead to a net increase in energy consumption and $CO_2$ emissions caused by overwhelming inefficiencies in cycling thermal power generation.[104] Solar PV is easier to manage than wind because its generation patterns are much more predictable and tend to match the energy demand profile, peaking during midday when energy demand is greatest. Concentrated solar power, which generates heat that can be stored in molten salt compounds, provides even more flexibility to grid operators.[105]

The increased deployment of hybrid gas-renewables “power parks” in recent years is testament to the two technologies’ synergies. Florida Power & Light Company, for instance, has completed the construction of a solar thermal plant that is colocated with an NGCC plant.[106] Baseline Wind LLC has submitted a proposal for a hybrid natural gas and wind power plant in Gilliam County, Oregon. In May 2011, General Electric announced plans to build a hybrid 530-megawatt NGCC-solar-wind power station in Turkey. Figure 9 lists some of the natural gas-renewables hybrid power plants that have been completed or are under construction.

Figure 9

| Project Name | Plant Operator | Total Capacity (MW) | Gas Capacity (MW) | Renewable Capacity (MW) | Location | Start Date |
|---|---|---|---|---|---|---|
| Martin Next Generation Solar Energy Center | Florida Power & Light Company | 1175 | 1100 | 75 (CSP) | Martin County, Florida | 2010 |
| ISCCS Ain Beni Mathar | Abengoa Solar/ Office National d'Electricite | 470 | 450 | 20 (CSP) | Ain Beni Mathar, Morocco | 2011 |
| H. Wilson Sundt Generating Station | AREVA Solar/ Tucson Electric Power | 161 | 156 | 5 (CSP) | Tucson, Arizona | 2013 |
| Chuck Lenzie Generating Station | NV Energy | 1195 | 1100 | 95 (CSP) | Las Vegas, Nevada | 2014 |
| Karaman Integrated Renewables Combined Cycle System | eSolar/ General Electric | 530 | 450 | 80 (wind and solar) | Karaman, Turkey | 2015 |
| Baseline Wind Energy Facility | Baseline Wind LLC | 700 | 200 | 500 (wind) | Gilliam County, Oregon | Uncertain |

Grid operators, state and federal agencies, and industry leaders should recognize the importance of flexible natural gas power plants in adding resilience to grid systems that are increasingly populated by intermittent renewables.[107] They should do all they can to ensure that gas and lower-carbon power sources continue to grow synergistically.[108] As Deutsche Bank Climate Change Advisors wrote in a 2010 modeling project, “by deploying ‘low risk’ fuel solutions such as gas, wind and solar in the next 20 years, the power system remains reliable and flexible keeping options open beyond 2030, by which time technology advances unknown today could still prove to be ‘game changers.’”[109] A recent Citigroup report agreed, calling the relationship between shale gas and renewables "symbiotic" and forecasting that gas would be "a transition to a lower carbon world" as renewables drop in price.[110]

The long-term consequences of building more gas power plants and increasing the utilization of existing gas capacity do not necessarily hinder gas' ultimate displacement by zero-carbon power. Upfront capital makes up a small portion of the levelized cost of gas-fired power generation. Approximately one-third of the levelized cost of an advanced combined-cycle gas plant is in capital equipment, while two-thirds of the total is in variable costs, including fuel. This stands in contrast to coal plants, where sunk investments pose a much larger obstacle to capital replacement.[111] Indeed, of all the major power technologies, combustion turbine and combined cycle natural gas have the lowest capital cost burden (see Figure 10).[112]

Figure 10

| Power Technology | Capital Cost |
|---|---|
| Natural gas (CT and NGCC) | $651–$1,230/kW |
| Onshore wind | $1,980/kW |
| Coal | $2,890/kW |
| Hydroelectric | $3,500/kW |
| Biomass (standalone) | $3,820/kW |
| Offshore wind | $3,150–$4,200/kW |
| Solar (PV and CSP) | $3,750–$6,530/kW |
| Tidal/wave | $4,360–$6,960/kW |
| Geothermal | $5,940–$9,900/kW |

Data from Black & Veatch's 2012 power technologies cost report prepared for the National Renewable Energy Laboratory. Figures are for plants going into operation in 2020. All figures use 2009 dollars.

## B. Cheap Natural Gas Does Not Significantly Alter the Trajectory of the Nuclear Power Industry

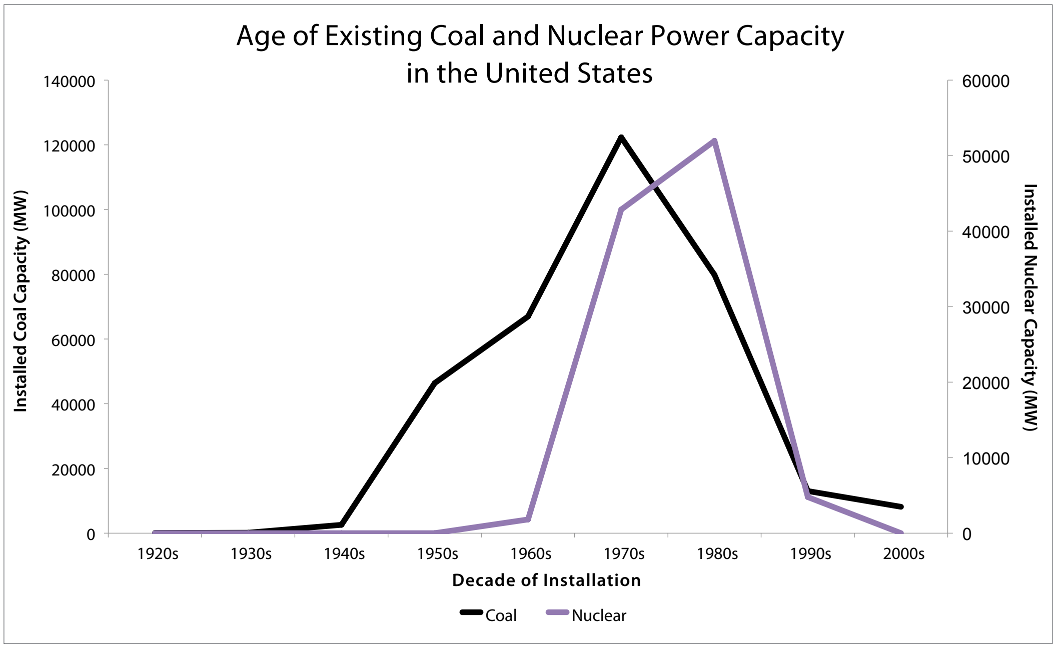
The gas boom has had a significant effect on coal-fired power, helping to bring about an 11 percent drop in coal's share of national electricity generation between 2007 and 2012 (from 48.5 percent to 37.4 percent). Yet it has thus far had no such effect on nuclear, which steadily produced about 19 percent US electricity over the same period.[113]

One reason for this difference is that existing nuclear plants generally provide cheaper electricity than either coal or gas. In 2011 the levelized cost of operation, maintenance, and fuel for nuclear plants was about 2.2 cents/kWh — compared to 3.2 cents/kWh for coal and 4.5 cents/kWh for gas.[114] In the majority of cases, after plant construction, the marginal cost of running a nuclear power station is less than that of coal or gas. High upfront capital costs and low fuel costs, in addition to technical challenges in ramping and cycling nuclear reactors, generally make it attractive for grid operators to keep nuclear plants running for as long as possible.

Yet the nuclear power industry is not immune to competition from cheap natural gas. Even though nuclear plants have lower variable costs, they may have higher overall annual costs due to significant fixed capital costs, which can make them economically uncompetitive with gas. In recent years, natural gas has contributed to the closure of two nuclear reactors in the United States. Both were near the end of their productive lives and were faced with regulatory compliance costs associated with aging or outdated infrastructure. Other factors were involved; one of the plants, for example, was scheduled to close because of a cracked containment dome.[115] Lower electricity market prices — driven largely by cheaper natural gas — made the capital investments necessary to keep the plants in operation unjustifiable.

As the nuclear power fleet continues to age, plant operators will be faced with more decisions about whether to retire nuclear plants or to invest in capital-intensive plant upgrades. As Figure 11 shows, the nation's existing nuclear fleet is much younger than the coal fleet, with a mean age of about 30 years as opposed to 40 years for coal plants. While a significant share of our existing coal capacity came online in the 1940s, 50s, and 60s, the bulk of nuclear power capacity wasn't installed until the 1970s and 1980s. As the nation's nuclear plants approach retirement age, more will need capital-intensive upgrades to remain operational and to maintain compliance with safety regulations. Much like with coal, the availability of cheap natural gas may diminish the appeal of keeping older nuclear power plants online.

Figure 11



Nevertheless, the shale gas revolution — and cheap natural gas — will not significantly impact the long-run trajectory of the nuclear power industry. Nuclear power faces several unique and significant burdens that predate and overwhelm the competitive pressure posed by the shale gas revolution. These include a complex regulatory process, lengthy construction times, high capital costs, frequent cost overruns, and public skepticism. Even if gas prices rise to their pre-shale boom levels, new nuclear will still be economically uncompetitive. The EIA's 2012 Annual Energy Outlook, for instance, estimates that the cost of new advanced nuclear power in 2017 will be 11 cents per kWh, compared to 6.3 cents per kWh for advanced combined-cycle natural gas power.[116]

The levelized cost of new nuclear plants has traditionally exceeded that of coal and gas, since well before the shale revolution. A 2003 MIT study, for instance, estimated that the cost of new nuclear power in the United States was 6.7 cents per kWh compared to between 3.8 cents per kWh and 5.6 cents per kWh for NGCC, depending on gas prices.[117] In 2009 the study was revised to reflect inflation and rising construction costs, bringing the estimated price of nuclear generation to 8.4 cents/kWh.[118] In general, new-build nuclear power is expected to be much more costly than natural gas or even coal (see Figure 12 below).[119]

The two Westinghouse AP1000 reactors currently under construction by Georgia Power (the first two plants under construction in the United States in more than 15 years) are expected to have total overnight capital costs in the $5,000-6,000/kW range (compared to the overnight capital cost of NGCC, approximately $1,000/kW).[120] As a result, the levelized electricity costs of these units will likely exceed 10 cents/kWh.

Figure 12

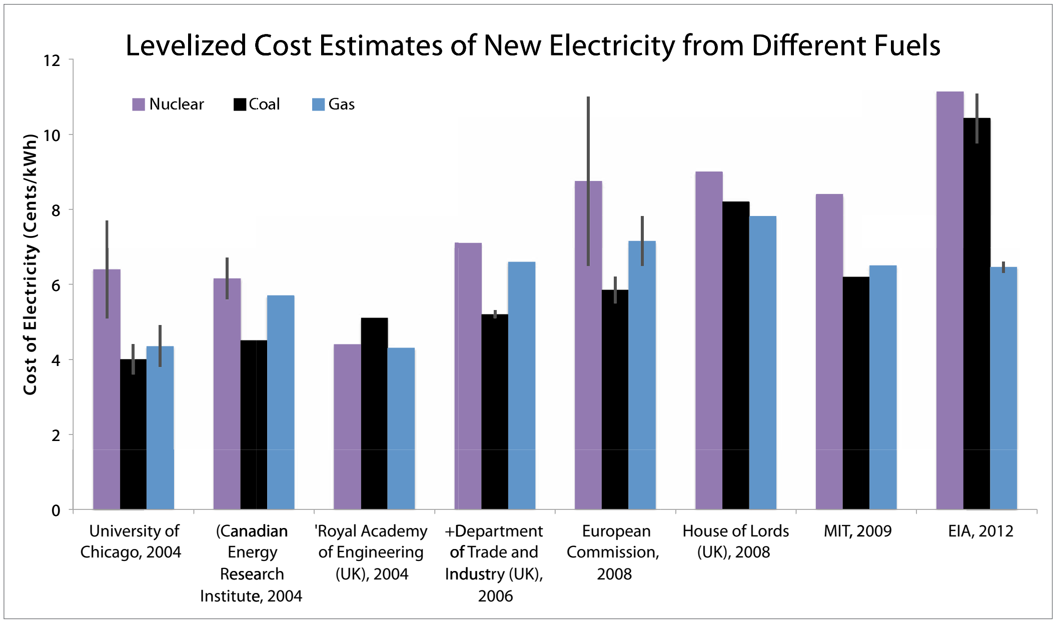


**Figure 12.** The graph above shows estimated average levelized costs for new nuclear, coal, and gas power plants, with cost ranges marked for those studies that included them.

Although cheap natural gas will impact the existing fleet to some degree, its impact on nuclear power will be minor when compared to its impact on coal. There may even be room for nuclear-gas synergy, such as matching flexible gas capacities with new base-load Gen IV+ reactors.

Given the high capital costs and complex regulatory environment associated with nuclear power, the revitalization of the industry will require a robust innovation policy support system. Such innovation will require moving beyond 20th century light-water designs toward nuclear power reactors that are increasingly cheap, modular, fuel efficient, and safe.[121]

## C. Taking Advantage of the Gas Revolution to Accelerate Carbon Capture Innovation

Scalable carbon capture technologies will prove essential in efforts to effectively mitigate global carbon emissions. Massive amounts of fossil energy reserves around the world will be exploited to meet global energy needs, even with accelerating deployment of zero-carbon options like renewables and nuclear. While carbon capture and sequestration (CCS) is often considered a prophylactic technology for coal-fired power plants, there are reasons to believe that immature CCS technologies can be more easily demonstrated and scaled on natural gas-fired power.

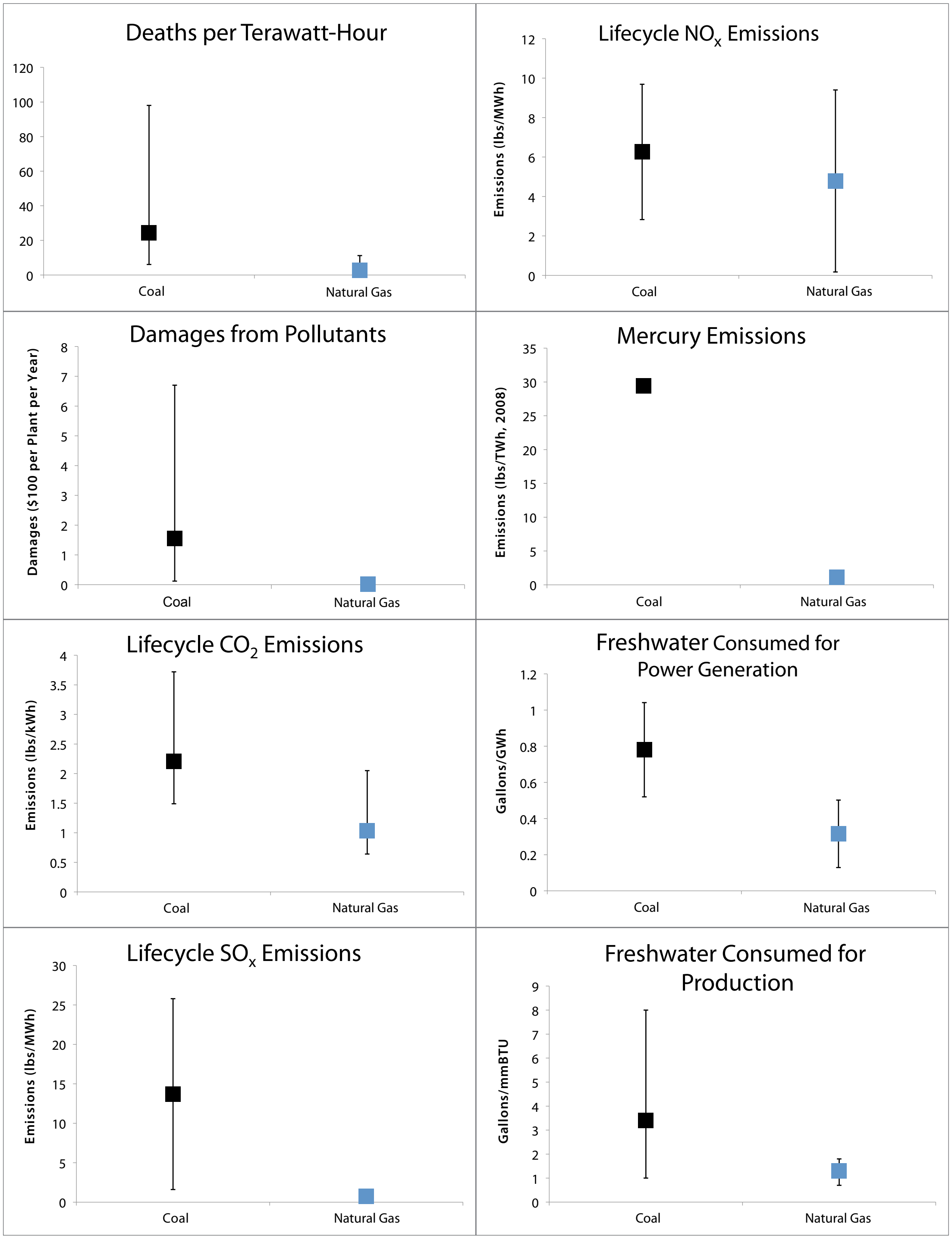
The separation and potential capture of carbon dioxide is an established practice in the natural gas industry. Drillers often must separate natural associated concentrations of $CO_2$ from natural gas resources, after which the $CO_2$ is typically vented into the atmosphere. But several industrial-scale CCS operations do exist, often for the purposes of using captured $CO_2$ for enhanced oil recovery.[122] Other such *use* practices may be exploited to increase demand for carbon capture technologies, including the application of $CO_2$ in petrochemical manufacturing, food and beverage industries, and the synthesis of artificial materials.[123]

Because the emissions stream of natural gas-fired power plants is much cleaner than that of coal-fired power, gas has considerable technical and cost advantages when it comes to capturing $CO_2$.[124] Recognizing this innovation opportunity, the Clean Air Task Force has recommended a series of "Pioneer Phase" demonstration investments to scale and reduce the costs of carbon-capture technologies.[125]

It is true that without a market value on carbon emissions, the widespread deployment of CCS technologies faces significant obstacles. But as with other technology-forcing policies — including sulfur-dioxide pricing in the 1990s that drove adoption of smokestack scrubbers[126] and the impending regulations on $CO_2$ from power plants in the United States — any regulation that requires CCS will very likely follow, not drive, the maturation of the mitigating technology itself.

# IV. Environment, Health, and Safety

Figure 13



Deaths per Terawatt-Hour

Lifecycle $NO_x$ Emissions

Damages from Pollutants

Mercury Emissions

Lifecycle $CO_2$ Emissions

Freshwater Consumed for Power Generation

Lifecycle $SO_x$ Emissions

Freshwater Consumed for Production

## A. Human Impacts

Coal is roughly eight times more lethal than natural gas. A comprehensive review of the public health effects of energy fuel cycles in Europe finds that coal causes 6 to 98 deaths per TWh (average 25 deaths per TWh), compared to natural gas's 1 to 11 deaths per TWh (average 3 deaths per TWh). These numbers include both accidental deaths and pollution-related deaths.[127] Coal mining is one of the most dangerous professions in the United States, resulting in 20 to 40 deaths annually, compared to 10 to 20 for oil and gas extraction.[128] Worker accident risk is also far higher with coal than with gas. In the United States, the oil and gas extraction industry is associated with one to two injuries per 100 workers each year.[129] Coal mining, on the other hand, contributes to four injuries per 100 workers each year.[130] Coal mines collapse, and can take down roads, water and gas lines, buildings, and many lives with them.[131]

Average damages from coal pollutants are two orders of magnitude larger than damages from natural gas. $SO_2$, $NO_x$, and particulate matter from coal plants create annual damages of $156 million per plant, compared to $1.5 million per gas plant.[132] Coal-fired power plants in the United States emit 17-40 times more $SO_x$ emissions per MWh than natural gas, and 1-17 times as much $NO_x$ per MWh.[133] Lifecycle $CO_2$ emissions from coal plants are 1.8-2.3 times greater (per KWh) than natural gas emissions.[134]

The air quality advantages of natural gas over coal have been borne out in Pennsylvania, according to studies by the RAND Corporation and the Pennsylvania Department of Environmental Protection. There, the shale boom has led to dramatically lower emissions of sulfur dioxide, fine particulates, and volatile organic compounds (VOCs).[135]

The most significant environmental impact of fracking shale for gas is the above-ground impact on communities. There are few instances of groundwater contamination as a result of fracking, and the causes of contamination — namely poor well completion practices — are known, fixable, and likely to be addressed over time as the gas industry and regulators improve compliance with best practices and as the industry and government agencies seek incremental improvements of drilling practices.

Local efforts to maintain a high quality of life for residents near gas operations should be encouraged, with a sense of pluralism and concern for conflicting interests and needs. A primary source of complaint from communities near fracking sites is the increase in heavy and loud trucks, traffic congestion, loud gas compressors on neighboring lands, local price inflation in response to the influx of new activity, and local air pollution. Much of the opposition to natural gas drilling is similar in character to the opposition to wind turbines and large solar farms, which also encroach on local landscapes and invite unwelcome construction.

State regulators must be responsive to community needs as well as environmental concerns. And policymakers nationally must seek to balance warranted local concerns about new development with the local, national, and global environmental benefits of moving from coal to gas.

## B. Landscape Impacts

Coal mining radically alters whole mountain and forest landscapes. Beyond the coal removed from the earth, large areas of forest are turned inside out and blackened with toxic and radioactive chemicals. There have been reclamation successes, but hundreds of thousands of acres of abandoned surface mines in the United States have not been reclaimed, and reclamation of certain terrain (including steep terrain) is nearly impossible.[136]

Where coal exploration requires altering landscapes far beyond the area where the coal is, aboveground natural gas equipment takes up just 1 percent of the total surface land area from where the gas will be extracted.[137] The environmental impact of gas drilling has changed radically in recent years. Vertical wells into conventional formations used to take up one-fifth of the surface area above the resource, a twentyfold higher impact than current horizontal drilling requires. A six-acre horizontal drill pad can thus extract gas from an underground area of 1,000 acres.[138]

The impact of natural gas on landscapes is even less, and shorter in duration, than the impact of wind turbines. The footprint of a shale gas derrick (3-5 acres) is only a little larger than the land area necessary for a single wind turbine.[139] But it requires less concrete, stands one-third as tall, and is present for just 30 days instead of 20-30 years. Between 7 and 15 weeks are spent setting up the drill pad and completing the actual hydraulic fracture. At that point, the drill pad is removed, leaving behind a single garage-sized wellhead that remains for the lifetime of the well.

## C. Water

Frack fluids and wastewater likely result in the most significant environmental damage associated with fracking, and should be the first element of unconventional gas production addressed by regulators. The challenges of groundwater contamination, wastewater treatment, and frack fluid reinjection are serious, and there are certainly cases of industrial misconduct and environmental abuse. However, these challenges can be mitigated by more-effective regulation, and new research suggests that hydraulic fracturing for shale gas is less water-intensive than both coal[140] and conventional gas production[141] on a per-unit energy basis.

With coal mining, waste materials are piled at the surface of the mine, creating aboveground runoff that pollutes and alters the flow of regional streams. As rain percolates through waste piles, soluble components are dissolved in the runoff and cause elevated total dissolved solids (TDS) levels in local water bodies.[142] Sulfates, calcium, carbonates, and bicarbonates — the typical runoff products of coal-mine waste materials — make water unusable for industry or agriculture and undrinkable for humans.[143] Acid mine wastewater can drain into groundwater, causing significant contamination.[144] Explosive blasting in a mine can cause groundwater to seep to lower-than-normal depths or connect two aquifers that were previously distinct, exposing both to contamination by mercury, lead, and other toxic heavy metals.

Contamination of surface waterways and groundwater with fracking fluids is rare. And since shale gas deposits are generally several thousand feet beneath groundwater concentrations and aquifers, groundwater contamination is also uncommon. Nevertheless, there have been instances of methane and frack-fluid migration, improper treatment of recovered wastewater, and pollution via reinjection wells.

### i. Frack-fluid and methane contamination of groundwater

There are relatively few verified cases of groundwater contamination linked directly to hydraulic fracturing. Those that have been recorded occurred near wells with inadequate cement casing or in regions where the fracking site and groundwater supplies are in abnormally close proximity.[145]

The reason for so little contamination is due to the fact that most shale plays reach depths of thousands of feet below the surface. In most cases groundwater aquifers are separated from the fracking site by hundreds or thousands of feet of rock. Geologists say it is nearly impossible for thickened fracking fluid to migrate thousands of feet upward through cracks in rock formations.[146] Nonetheless, poor well casings or improper disposal of wastewater have resulted in freshwater contamination and must be addressed by environmental regulators. Reinjection wells in Colorado, for instance, have been shown to pollute deep drinking water aquifers. This practice, implicitly sanctioned by an EPA exemption for fracking under the federal Safe Drinking Water Act, should be minimized as much as possible. While applications for exemption require proof that contaminated water is out of reach for human consumption, experts have questioned the reliability of the approval process.[147]

Methane that leaks into water supplies is not toxic, but it can be a hazard, whether it is caused by natural forces or by gas drilling. In a small number of cases, fracking has led to increased concentrations of methane in groundwater supplies, including in 2010 in Dimock Township, Pennsylvania,[148] and near Pavillion, Wyoming.[149] There is empirical evidence for fracking-related methane groundwater contamination in Pennsylvania and upstate New York,[150] but these types of incidences pose little threat to public health and do not appear to be widespread.[151] Because groundwater and aquifer methane contamination occur overwhelmingly along the vertical wellbore, there is little increased risk from horizontal shale drilling in deep shale deposits.

### ii. Surface wastewater contamination

There have been reports of higher-than-normal fracking-related chemicals in bodies of water where flowback fluid has been discharged, and aboveground fracking fluid spills that have contaminated groundwater. In some cases, flowback water is treated at municipal wastewater treatment plants, and then discharged into regional water bodies.[152] In 2008 and 2009, for instance, TDS levels exceeded drinking water standards along Pennsylvania's Monongahela River, a major source of drinking water that was receiving discharges from flowback water treatment facilities.[153] Increased TDS levels in rivers and waterways can make those ecosystems inhospitable for aquatic life and unusable for human use.

While there have been accidents, fracking wastewater is not difficult to contain and dispose of. Wastewater from fracking is either treated before entering water bodies or pumped underground and away from aboveground water sources.[154] Wastewater from hydraulic fracturing can be reinjected one and a half miles below the surface in the Barnett shale in Texas but not in the Marcellus shale in Pennsylvania, where the rocks are not as porous. Where it cannot be reinjected, flowback water is temporarily stored in pits, embankments, or tanks at the well site after the frack job, and then transported (usually via pipeline or truck) to a treatment or disposal site. Storage in pits can lead to groundwater contamination, particularly if the pits are unlined or if the integrity of the lining is compromised. After pit storage, flowback water is typically transported via pipeline or truck for disposal or, in some cases, treatment. In the majority of disposal cases, flowback water is injected into deep porous rock formations, such as sandstone or limestone, or into or below the shallow soil layer,[155] posing a risk for groundwater contamination.

But surface water contamination is generally associated with water resources downstream of treatment facilities, not shale wells. Research by experts at Resources for the Future found little trace of contamination downstream from drilling sites, and contamination downstream from wastewater treatment facilities was more significant but considered manageable.[156] As the shale gas extraction industry and regulatory environment mature, the nation should expect and insist on improved practices with respect to water use and wastewater treatment.

### iii. Water intensity of energy production

In most cases, both life-cycle water intensity and pollution associated with coal production and combustion far outweigh those related to shale gas production.

Coal resource production requires at least twice as much water per million British thermal units (mmBTU) as does shale gas production.[157] And while regions like Pennsylvania have experienced an absolute increase in water demand for energy production thanks to the shale boom, shale wells actually produce less than half the wastewater per unit of energy compared to conventional natural gas.[158]

Coal-fired power plants consume two to five times as much water as natural gas plants. Where 520-1040 gallons of water are required per MWh of coal, gas-fired combined cycle power requires 130-500 gallons per MWh.[159] The environmental impact of water consumption at the point of power generation depends on the type of power plant: plants either use evaporative cooling towers to release excess heat, or they discharge water to nearby rivers.[160] Plants using natural gas combined-cycle power (NGCC), which captures the exhaust heat generated by combusting natural gas to power a steam generator, are considered the most efficient large-scale thermal power plants. One study found that the life-cycle demand for water from coal power in Texas could be more than halved by switching the fleet to NGCC.[161]

All told, shale gas development in the United States represents less than half a percent of total domestic freshwater consumption, although this portion can reach as high as 25 percent in particularly arid regions.[162] All energy development impacts will have varying effects on different local communities, and these should be considered when crafting regulations and industrial best practices. Yet the clear and substantial public health and environmental advantages that shale gas has over coal provide sufficient justification to support the continued development and improvement of unconventional gas drilling.

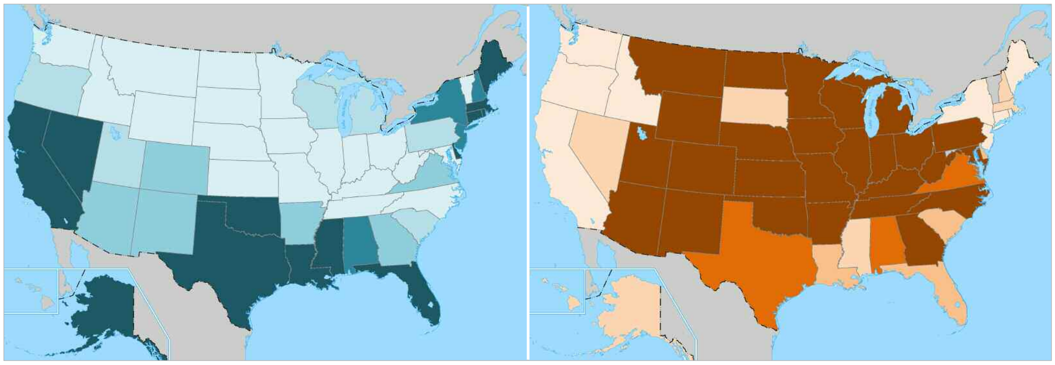
# V. Policy Recommendations

## A. Accelerate the coal-to-gas shift in the United States.

In light of the clear climate, environmental, and energy-systems benefits of the ongoing shale gas revolution in the United States, governments at the state and federal level should pursue policies that accelerate the shift from coal to natural gas.

The two maps in Figure 21 show the percentages of natural gas and coal-fired electric power supplied by each state. In regions where coal supplies much higher portions of electricity than gas, such as in the Midwest and Great Plains states, coal power plants should be taken offline as wind grows. Baseload, load-following, and peaking natural gas power plants should be simultaneously utilized and expanded to add resiliency and spinning reserve capacity to the grid.[163]

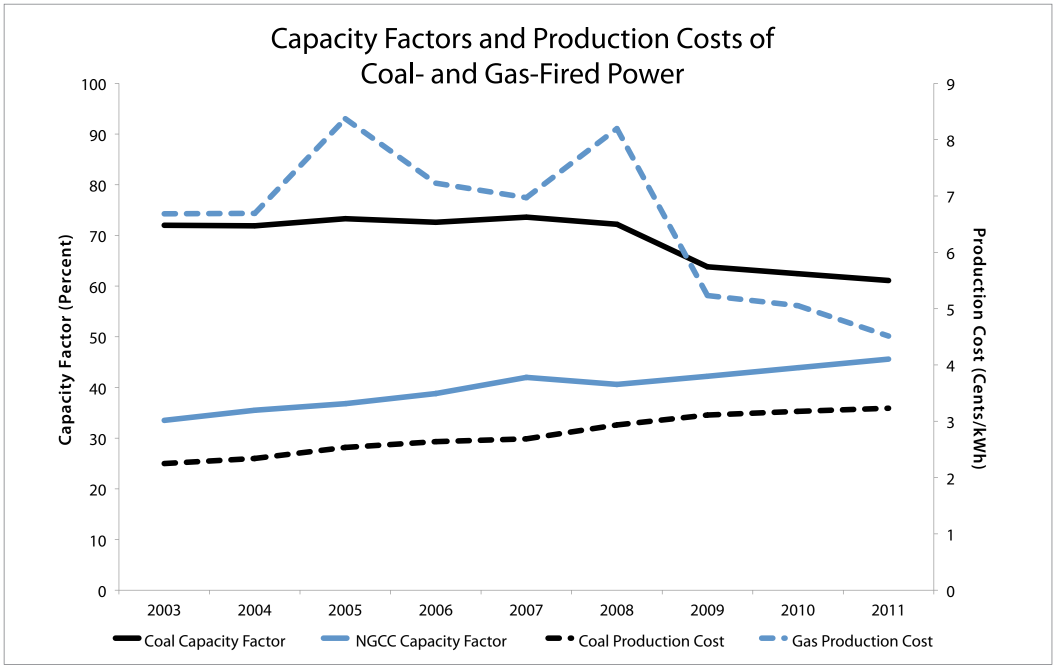
Figure 21



The left map shows state-level intensity of gas as percentage of total electric power generation (darker blue represents more gas); the right map shows state-level intensity of coal as percentage of total electric power generation (darker brown represents more coal). Data from the US Energy Information Administration. Source: US Energy Information Administration and the Nuclear Energy Institute.

Where gas and coal compete more directly, such as in Texas and Virginia, policies should reinforce the switch from coal to gas — allowing gas and next-generation nuclear to displace coal as the provider of baseload power, and bolstering gas's role in providing load-following and peaking power to the grid. Nevada, for instance, recently initiated regulatory reforms to fully phase out coal generation in the state.[164] This approach creates the opportunity for intermittent renewables to increase their share in the electricity mix without overwhelming the grid, and also accelerates the decarbonization of the electricity sector.

## Figure 22



Historically-low prices have made natural gas more attractive than coal. Figure 22 shows that as the price of gas has declined the gas fleet's nationwide average capacity factor (the ratio of actual output to potential output) has increased, with the opposite trend occurring for coal. Between 2003 and 2011 the nationwide average capacity factor of natural gas combined cycle plants jumped from 34 percent to 46 percent. Over the same period, the nationwide coal capacity factor has dropped from 72 percent to just over 60 percent.

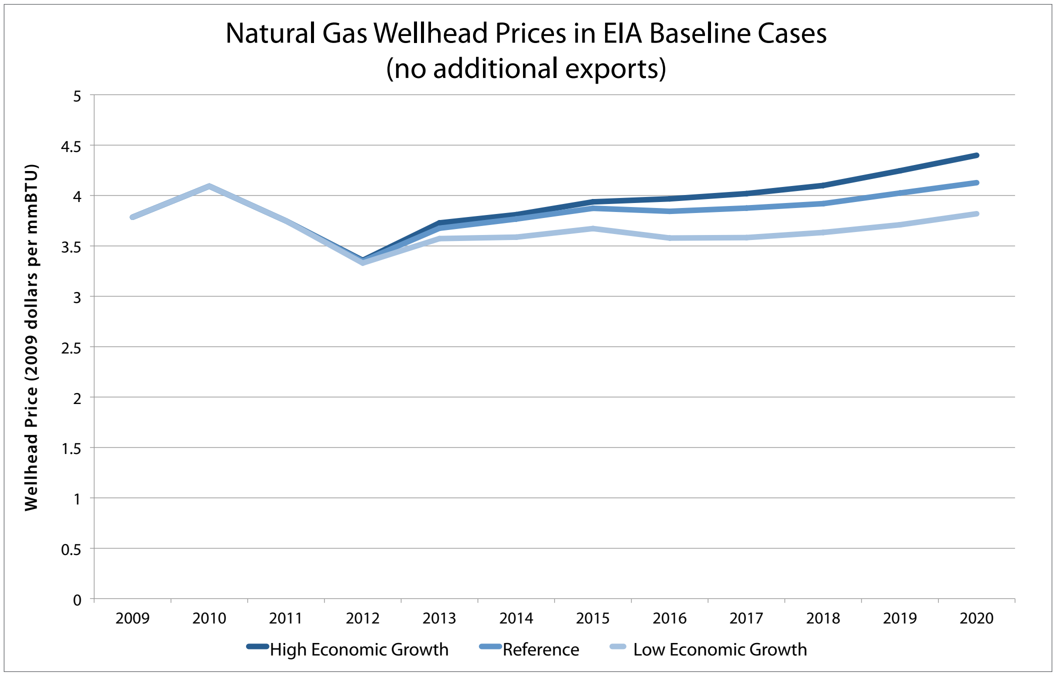
Federal and state governments should **ensure that as the price of natural gas rises from its current unsustainable low, economic and regulatory incentives remain to sustain the displacement of coal by cleaner and cheaper natural gas.** States should pursue deals with electric utilities requiring them to incorporate natural gas into the mix (as Colorado has done with its largest electric utility, Xcel Energy) or embed gas capacity as firming power into state Renewable Portfolio Standards to maintain system reliability. At the federal level, the creation of a Clean Energy Standard that includes both natural gas and nuclear, or the implementation of a modest tax on power-sector carbon emissions, would accelerate the transition. The federal government should also strengthen EPA regulations through the Clean Air Act, requiring new power plants to meet stringent $CO_2$ emission standards, and should follow through on its mandate to extend these standards to existing plants.[165]

Policy actions that ensure robust, long-term markets for domestic gas resources should be explored. One option to stabilize long-term prices at sustainable levels would be for the federal government to **approve a limited and strategic volume of natural gas for export.**

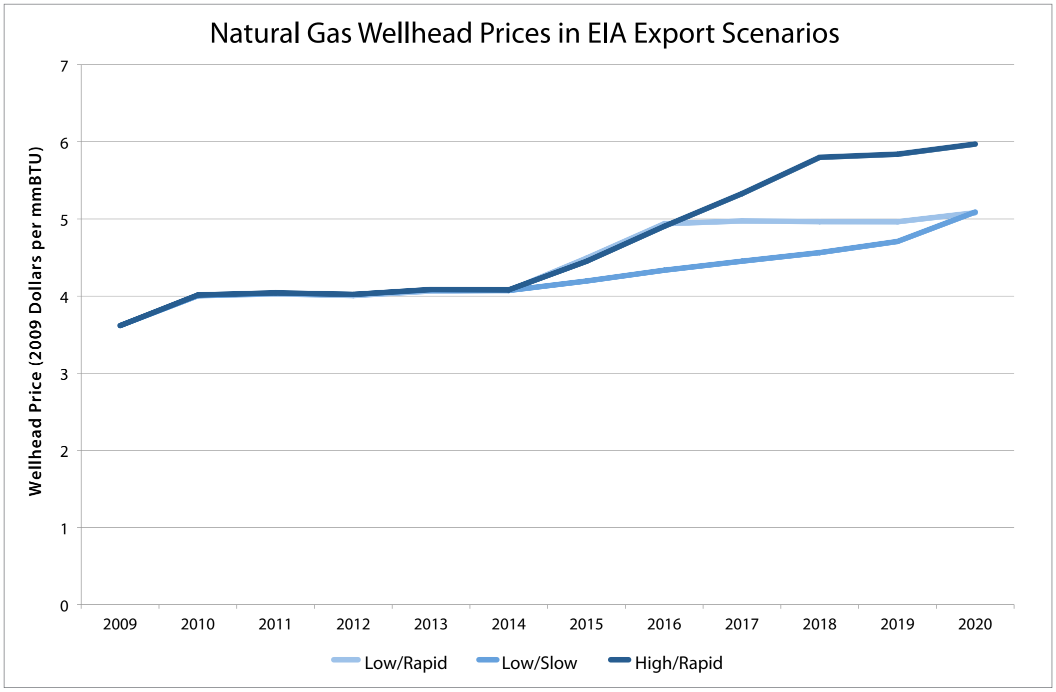
Experts expect that approval of a limited amount of liquefied natural gas (LNG) for export will have a minor effect on prices and domestic consumption while providing other long-term customers to gas producers. The Department of Energy and the Federal Energy Regulatory Committee, which oversee application and approval of natural gas exports, should consider the impact that strategic volumes of export can have on the domestic coal-to-gas shift in the United States.

As recent modeling commissioned by the US Energy Information Administration shows, natural gas exports would increase economic growth and net domestic gas production, because the majority of exported gas is expected to come from increased production.[166] The EIA also concludes that exports would raise natural gas prices from their current low levels, stabilizing them within the $4-6 per million British Thermal Units (mmBTU) price band that many producers say is necessary to cover marginal production costs.[167] Analysts agree that while exports would impose some upward pressure on domestic gas prices, the magnitude of price increase resulting from 6-10 billion cubic feet (bcf) of exports will happen regardless, as US gas markets reach equilibrium.[168, 169, 170, 171]

## Figure 23



## Figure 24



Although the approval of LNG exports will have a limited economic impact, it is an important policy for the sustained growth of natural gas production in the United States. Exports are not expected to significantly increase prices, but will help to provide enough of a price increase to allow gas developers to operate profitably.[172]

## B. Ensure a steady gas supply by establishing clear, effective regulations for safe and productive exploration.

Addressing the environmental challenges associated with hydraulic fracturing — avoiding groundwater contamination, ensuring safe wastewater disposal, minimizing landscape and ecosystem damage, limiting fugitive methane emissions, and others — should be a chief priority of regulators. Smarter, stringent regulation would ensure that local industrial activities are safe and provide reassurance to communities.[173]

Gas development majors and large independent gas producers also favor effective regulation. While potentially raising operations and compliance costs, regulation ensures that drilling operations are safe and sustainable. Regulation also prevents smaller wildcatter developers from skirting compliance measures.[174]

Regulators should look to best practices in states with experience overseeing oil and gas industries, including Texas, Pennsylvania, Virginia, and North Dakota. Some states where shale gas production occurs have regulations pertaining to the type of cement that must be used and the minimum distance that cement must be applied to the well casing.[175] In Pennsylvania, for instance, casing must be cemented with an ASTM International-approved cement to a minimum of 50 feet deeper than the deepest fresh groundwater.[176] All shale-producing states should consider similar regulations.

Regulators should enforce rules requiring shale developers to seal wells properly to prevent groundwater contamination. Heavy fines for methane migration due to poor cement jobs should be enforced. Moreover, regulators should strictly enforce rules requiring wells to be sited at a safe distance away from residential and municipal wells, freshwater springs, streams, and wetlands. Most states, including Pennsylvania, New York, Texas, Oklahoma, Ohio, Michigan, and Arkansas are already in the practice of enforcing safe well-completion and distancing practices.[177]

With the practice of shale fracturing spread across so many states with different regulatory regimes, a role for federal regulation will prove essential. The EPA should coordinate state regulation and work to transfer technical and experiential knowledge from states with extensive institutional knowledge about drilling (such as Texas) to states with less experience in fuel production, such as New York and Ohio.

A consortium of energy companies and environmental advocacy organizations has established a model for state and federal regulations over shale gas. The Center for Sustainable Shale Development — with partners including the Clean Air Task Force, the Environmental Defense Fund, Shell, and Chevron — has outlined a series of best practices to ensure that the industry meets social and environmental standards. These include a 90 percent water-recycling requirement, tight well casing standards, and hard limits on discharge of gas into the air at the point of extraction.[178]

## C. Export hydraulic fracturing technical expertise to nations and regions where knowledge and expertise is limited.

Despite a decline in domestic coal consumption as the result of the shale gas revolution, coal is the world's fastest growing fuel source, led by huge increases in demand in Chinese and Indian electric power markets. Under business-as-usual projections, coal is expected to overtake oil as the world's most consumed energy source within five years.[179] The global availability of shale gas offers tremendous promise to offset a portion of the greenhouse gas emissions that will be associated with the global expansion of fossil-fueled power. The EIA estimates that China, for instance, is sitting on 1,275 trillion cubic feet of shale gas, compared to an estimated 543 trillion cubic feet in the United States.[180]

However, most countries lack the technological, institutional, and regulatory experience that has made the shale gas revolution possible in the United States. **American and international development institutions should work toward the development of shale gas industries in other nations.**

The World Bank, the US Export-Import Bank, and the Overseas Private Investment Corporation (OPIC) should favor shale and other natural gas resources over coal projects. Cabinet-level tech transfer offices should facilitate the export of safe fracking technologies and techniques. Development agencies should actively promote emerging gas resources in energy-scarce regions as a means to boost local energy supply, displace current or future coal production, and provide a platform for electricity growth and innovation that includes renewables and other low-carbon technologies.

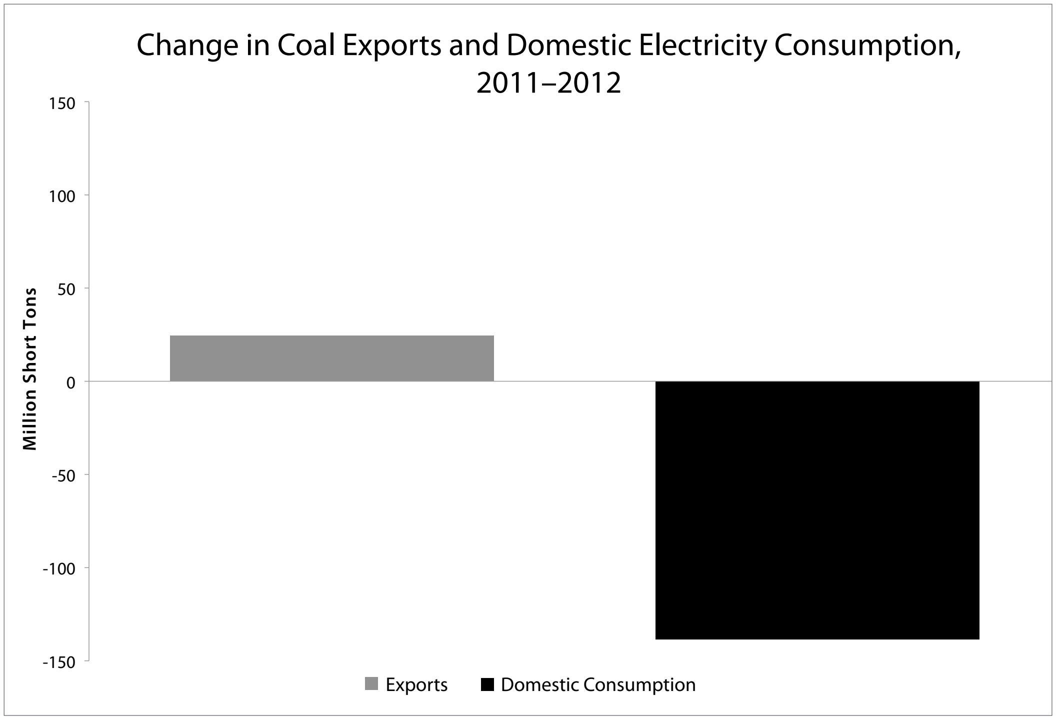
In 2010 the US State Department launched the Unconventional Gas Technical Engagement Program (UGTEP) to help countries seeking to develop their shale gas resources.[181] UGTEP works with host governments, and its activities are tailored to each country's specific needs and availability of funding. In the past, UGTEP has conducted shale gas resource assessments; technical guidance to evaluate production capability; and workshops and seminars on the technical, environmental, business, and regulatory challenges that are associated with shale gas development. Initiatives such as these should be maintained and strengthened.

## D. Limit exports of domestic coal resources.

As US international development agencies work to expand energy access and initiate domestic gas exports, the federal government should also limit the export of coal to international markets. A portion of the emissions progress made by the switch from coal to gas in the United States is eroded by carbon leakage, as coal volumes not burned in America are shipped abroad. In 2003, the US exported some 43 billion tons of coal to countries around the world. In 2008, by which point cheap gas had begun to drive coal out of the market, the country exported 82 billion tons of coal. And in 2011, the US exported an estimated 107 billion tons.[182] However, increased exports have nowhere near offset the decline in domestic coal consumption. For example, as Figure 25 shows, exports in 2012 were 25 million tons higher than in 2011. Domestic consumption, meanwhile, decreased by 140 million tons in 2012.

Nonetheless, the United States should take all possible steps to limit export of domestic coal resources. One option would be to place a license requirement for exports of raw coal commodities from the United States, similar to the Department of Commerce requirement for crude oil exports.[183] The construction and operation of coal export facilities are also excellent targets for climate and environmental activism.

Figure 25



## E. Pay it forward.

Each year since at least 2009, lower natural gas prices due to the shale gas revolution have resulted in more than $100 billion of additional economic surplus.[184] A study by the economic research firm IHS found that unconventional oil and gas activity generated $61 billion in federal and state revenues in 2012, and estimates that this figure will increase to $91 billion in 2015 and $111 billion in 2020.[185]

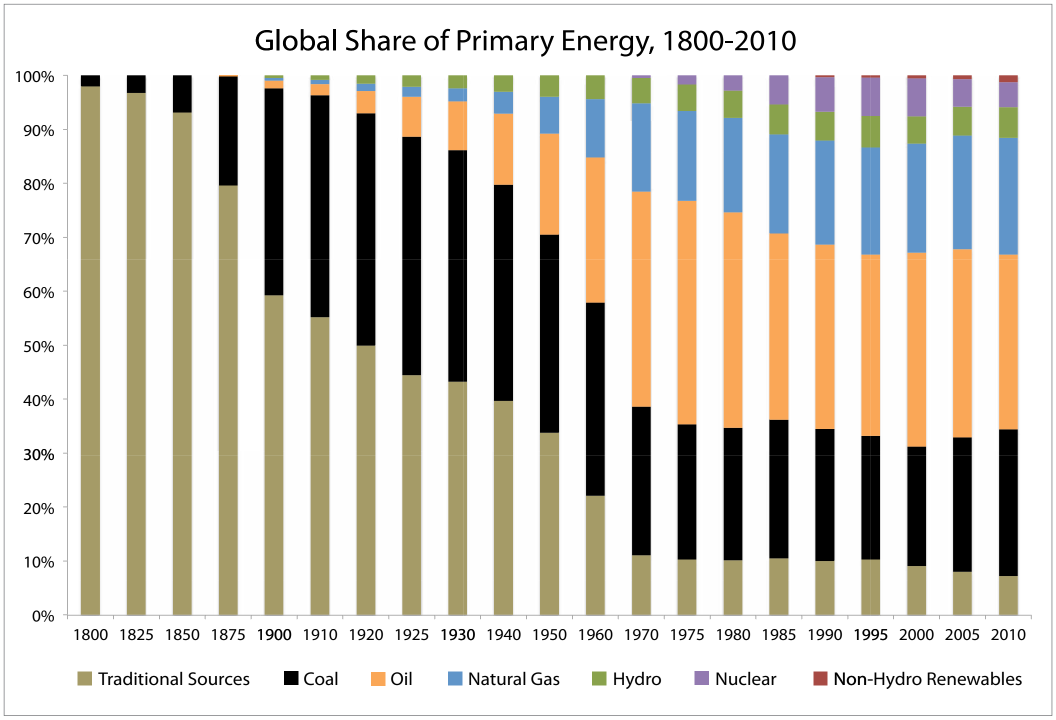
The expansion of natural gas must be accompanied by the development and deployment of other renewable energy technologies — wind, solar, biomass, advanced biofuels, advanced batteries and other storage technologies — as well as advanced nuclear and carbon capture and sequestration technologies. The Obama administration and members of Congress have already recognized the necessity of paying it forward, advancing policies that would allocate portions of unconventional oil and gas drilling revenues for clean energy technologies.[186] Proposals such as these should be encouraged and advanced vigorously at both federal and state levels.

The implications of paying it forward are enormous. The shale gas revolution is the result of decades of targeted public and private expenditure on advanced energy technologies and techniques. Within the next few years the shale gas revolution will have contributed more to the US economy than all federal expenditures on all energy industries since 1950.[187] We should not underestimate the future benefits of investment in advanced energy technologies today.

# VI. Conclusion

The transition from coal to natural gas is not unique. The replacement of dirtier, more expensive, and otherwise inferior energy technologies by newer, better, cleaner, and cheaper ones is characteristic of all significant energy transitions to date. Wood was central to human development, as humankind's primary energy source for at least two millennia. Fire increased the physical security of human communities, allowed us to cook hunted animals, increased the amount of protein that we could absorb, and helped us develop smaller intestinal tracts and larger brains.[188] But increasingly-large human populations using wood for fuel resulted in widespread deforestation, including the denudation of Europe by the 18th century. Indeed, new research finds that 75 percent of all human-caused deforestation occurred before the 19th century.[189]

Figure 26



Even so, what led to the replacement of wood energy was not the exhaustion of forests but rather the emergence of a cheaper and better alternative — coal, the consumption of which increased tenfold in the last 50 years of the 19th century. One of the oftexpressed fears of critics of natural gas production is that natural gas consumption will simply expand on, rather than reduce, coal use. But if the transition from wood to coal is any guide, older fuels will be replaced more quickly than they are supplemented.

While today we tend to focus on coal's environmental harms, it is worth recalling that it replaced hazardous wood-cooking smoke with electricity, contributing as well to reforestation. Because of the expanded use of coal and other fossil fuels, total available global energy increased 25 times between 1900 and 2000,[190] boosting global living standards and life expectancy. Coal was such a popular alternative to wood in the late 19th century that state governments promoted coal production, just as the federal government promoted fossil fuel alternatives to whale oil during the same period, and for similar reasons.

Coal's longstanding advantages remain: its abundance, its low costs, its reliability as a source of baseload power, and the low levels of technical expertise required to convert it to energy. Ensuring affordable energy access remains one of the highest priorities of policymakers in developing and developed countries alike, and as long as coal is the cheapest source of baseload power it will remain king.

While some historians and analysts have treated the shale gas revolution as emerging *deus ex machina* from the free market, it was in truth greatly aided by federal subsidies for development, demonstration, and deployment — just as the coal and kerosene revolutions were subsidized 100 years earlier. This is not to suggest that public subsidies were the determining factor — the energy density and relative cleanliness of the newer alternative were also key factors. But public policy and subsidies in all these cases accelerated the pace at which superior technologies were developed and deployed.

This history has important implications. If energy transitions are not automatic — if they are instead created and aided by public investments and institutions — then policymakers should keep one eye on replacing coal with gas and the other on supporting the development of technologies to succeed gas. To a large extent, this has long been what the United States has done, by supporting the development of natural gas, nuclear, and renewables even while coal use expanded during the 20th century. Viewed from the perspectives of history and technology, the natural gas revolution is best understood as a moment in the process of energy modernization and innovation, not its end point.

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    The total potential US export capacity is 20.3 bcf per day. If this full export potential were realized it would amount to between 19 and 25 percent of US domestic gas demand in 2011. Few observers, however, expect all or even most of this export capacity to be realized due to political and economic constraints.

    The potential economic benefits of exporting natural gas have been noted. One study finds that overseas sales of exported natural gas could provide an annual additional $4 billion in US economic output and $20 billion in export revenues, as well as the near-term creation of 8,000 jobs and long-term creation of 60,000 jobs across the natural gas production and supply chain.

    If exports are limited to approximately 6 bcf per day (as is likely in the near-to-medium term), then the US would only be exporting about 7 percent of its current production, and prices would probably not increase beyond an additional $0.70 per mmBTU.

    While the EIA does not expressly consider the impact of exports on the price of natural gas inputs in the manufacturing sector, modeled price increases show that the impact will not be severe. The EIA models suggest that if exports are allowed to proceed, gas prices in 2035 will range from 6.4 to 14.6 percent higher than today's prices.

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