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HYDRAULIC FRACKING: A STORY OF AMERICAN INNOVATION

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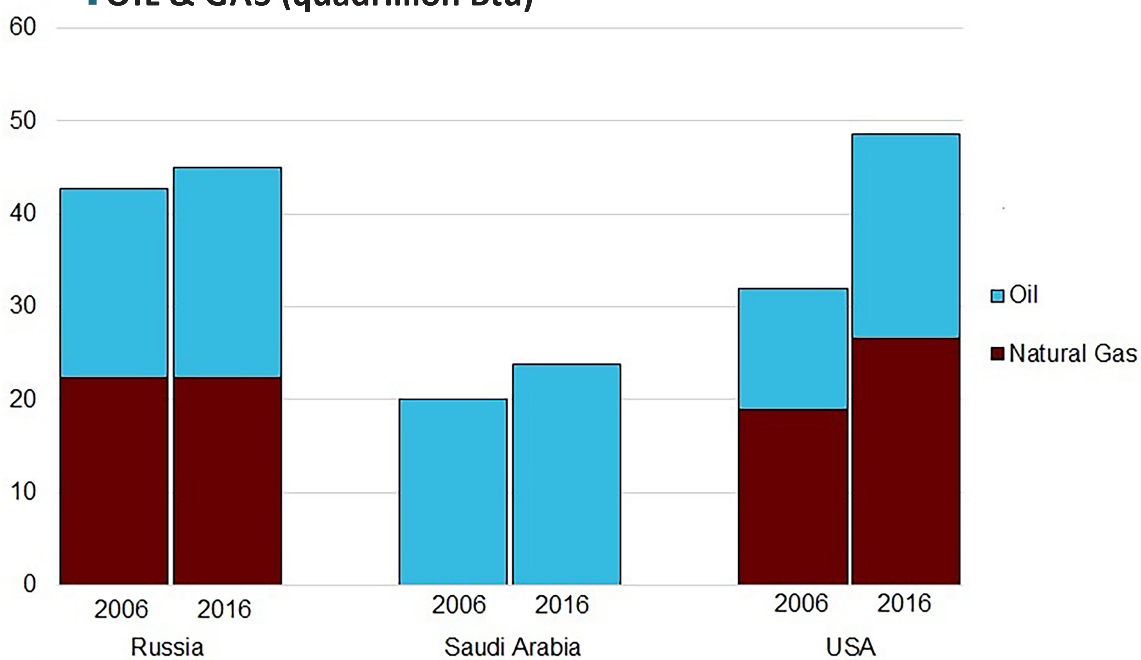
It is favorable to assume that a random person on the street would tell you that the country producing the most energy from oil and gas is Saudi Arabia. This, however, is incorrect. The de facto head of the OPEC cartel, though frequently in the news, is not the biggest producer, nor even the second largest. Perhaps surprisingly, the United States currently holds that distinction, and by a decent margin. As seen below in Figure 1, the United States produced over 49 quadrillion Btu of energy from oil and gas production in 2016, leading Russia by nearly 5 quadrillion Btu, or almost 10% of USA output. Saudi Arabia lags behind at roughly 25 quadrillion.

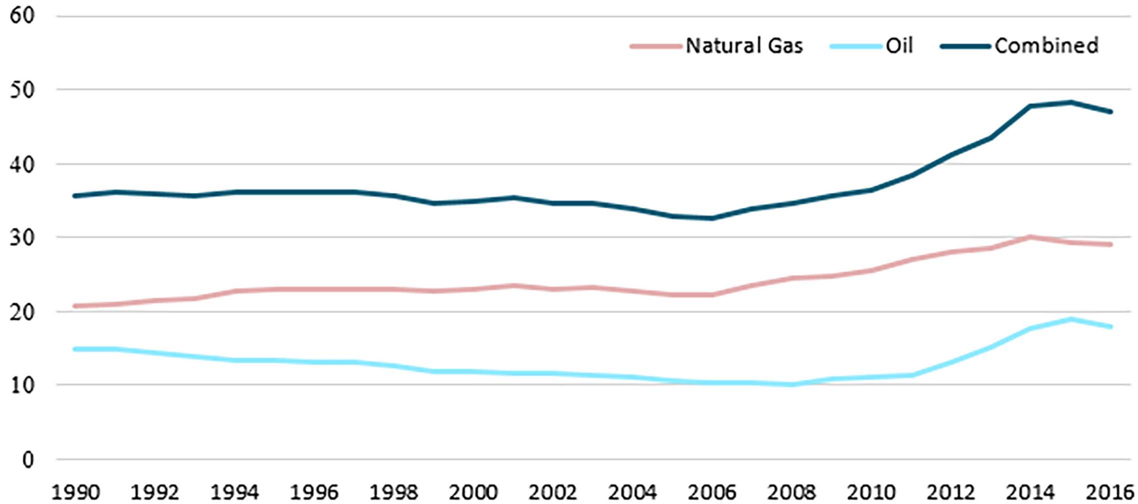
FIGURE 1. NATIONAL ENERGY PRODUCTION FROM OIL & GAS (quadrillion Btu)



Source: EnerData: Global Energy Statistical Yearbook 2017 - Natural Gas Production (Link), EnerData: Global Energy Statistical Yearbook 2017 - Crude Oil Production

It is clear that the U.S. advantage over Saudi Arabia comes from production of natural gas. Despite massive oil production, Saudi Arabia produces less than 1% of total energy from oil and gas. In comparison, U.S. natural gas accounts for nearly 60% of the total energy production from oil and gas.

FIGURE 2. U.S. ANNUAL ENERGY PRODUCTION FROM NATURAL GAS & OIL



Source: Energy Information Association: Natural Gas Gross Withdrawals and Production (Link), Energy Information Association: Crude Oil Production

The United States has not always held the top spot. In the past, Russia dominated, producing roughly 43 quadrillion Btu of energy. The U.S. produced just 32 quadrillion Btu. Fast forward 10 years, and the United States was able to increase total production from 32 to 49 quadrillion — an increase of more than 50%. In the same time frame, Russia and Saudi Arabia saw only marginal increases in their production.

Figure 2 presents annual data on oil and natural gas production in the U.S., as well as total Btu production, from 1990 to 2016. In the graph, total Btu production was either stagnate or decreasing from 1990 to 2006, largely because of a declining production of oil. However, starting in 2007 the U.S. experienced a steady increase in total production, with natural gas leading the way. In 2011, oil production began rising as well, adding to the growth in total Btu production, which reached an all-time high in 2015.

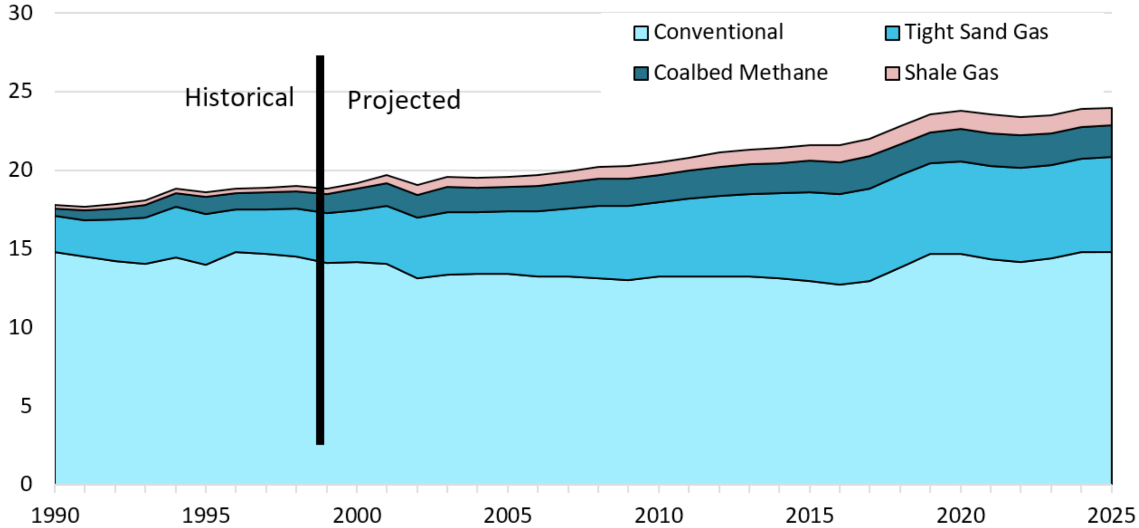
How did the U.S. reverse the long run trend of decreasing production, and in less than a decade achieve a 50% increase in production of oil and natural gas? The answer can be summarized in two words: hydraulic fracking.

BACKGROUND

The basic concept of hydraulic fracking is relatively simple and has existed since the 1950s—a rock, generally shale, is fractured by the injection of pressurized fluids in order to release natural gas and petroleum for collection. Hydraulic fracking was a natural progression from the original means of fracking, which used gunpowder and other explosives to shatter the shale and release the gas and oil. However, prior to the 2000s, this technique was rarely used as it was costly and did not produce consistent results. Historically, natural gas production from shale accounted for a minute percentage of the United States' total production.

Each year the U.S. Energy Information Administration (EIA) produces a report, the Annual Energy Outlook. This document provides an overview of U.S. energy issues, and among other information provides a forecast of where natural gas will be sourced in the future. Figure 3 shows these projections made in the Annual Energy Outlook in 2004. This issue provided historical data on the sources of natural gas produced in the U.S. from 1990-2002, and the EIA's projected sources of natural gas going forward, from 2003 to 2025.

FIGURE 3. SOURCES OF NATURAL GAS PRODUCTION IN THE UNITED STATES 1990-2002, WITH PROJECTIONS TO 2025 (trillion cubic feet)



Source: Energy Information Association: Annual Energy Outlook 2004

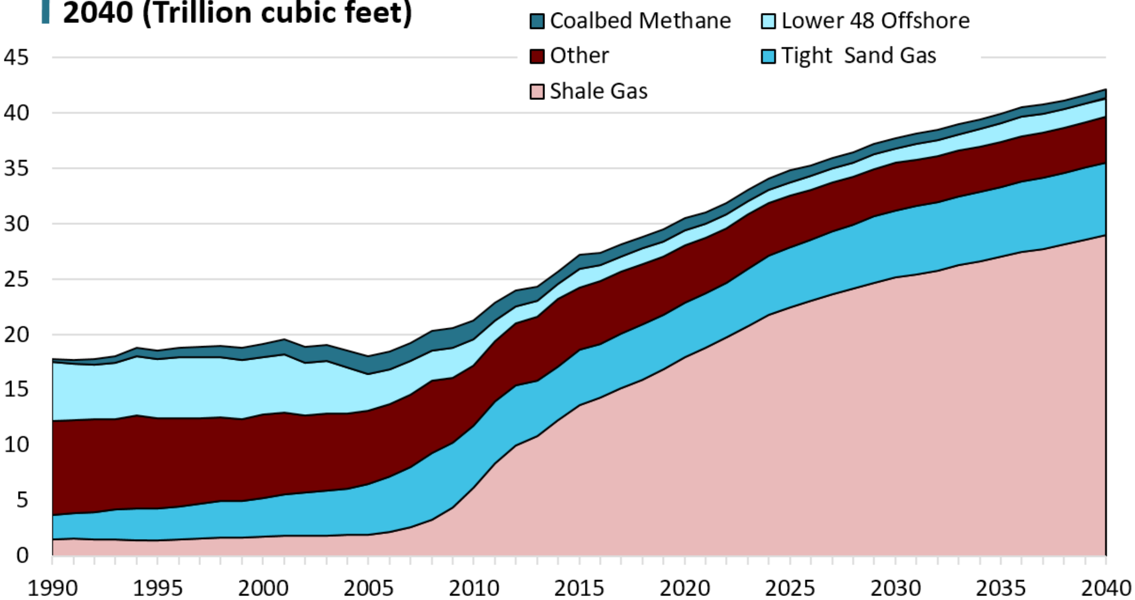
In 2004, natural gas production from shale accounted for a small fraction of the total amount produced. The EIA did not expect natural gas production from shale to increase by a noticeable amount over the forecast period. At the time of this report, the majority of natural gas extraction was through conventional methods, both onshore and offshore. In this context, conventional means that the gas was acquired through the traditional means of drilling a vertical well down into a suspected gas reservoir, and letting the gas flow freely to the surface for collection. In the 1990s and early 2000s, this was the dominant means of collecting natural gas, and as the 2004 projections show, the status quo was not expected to change any time soon.

As history has shown, these 2004 projections turned out to be very inaccurate when compared to actual production and highlights the importantance of the innovations that changed this industry. Figure 4 shows graphs data from the EIA's Annual Energy Outlook from 2016, with historical data from 1990 through 2015, and projections from 2015 to 2040. The shale gas category accounts for the vast majority of projected natural gas production. Further, the increase in shale production in the historical period clearly accelerated in 2007 to 2008, and by 2015, already accounted for the majority of U.S. natural gas production. The change from Figure 3 shows the unexpected rise of shale gas production and also how shale gas production is projected to grow in the future.

Note the changes in nomenclature over time. What was once labeled "Conventional" has now been split into "Other" and "Offshore". What was once the primary source of natural gas is now listed as "Other."

Wang and Krupnick (2013) put this change into numbers. They write that "In the past decade, shale gas experienced an extraordinary boom in the United States, accounting for only 1.6 percent of total US natural gas production in 2000, 4.1 percent by 2005, and an astonishing 23.1 percent by 2010." In explaining this change, Wang and Krupnick cite an unforeseen confluence of factors including high natural gas prices, favorable geology, private land and mineral rights ownership, market structure, legal changes, natural gas pipeline infrastructure, and most importantly, several key innovations in technology.

FIGURE 4. SOURCES OF HISTORICAL NATURAL GAS PRODUCTION IN THE U.S. 1990 - 2015, WITH PROJECTIONS TO 2040 (Trillion cubic feet)



Source: Energy Information Association: Annual Energy Outlook 2016

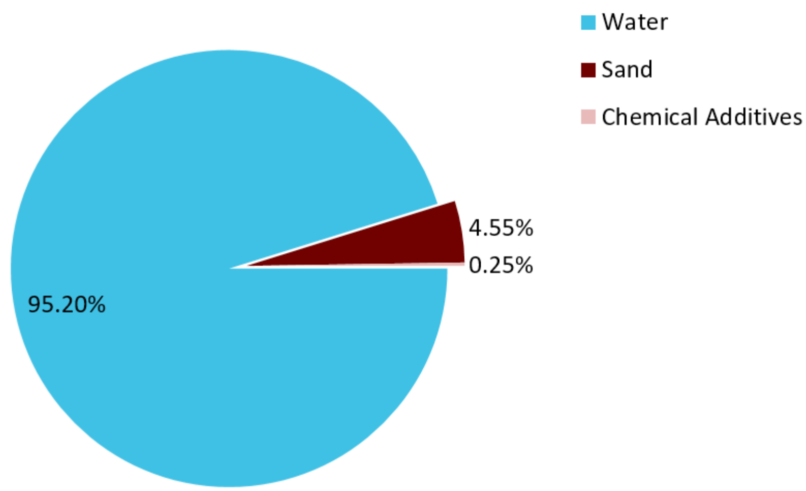
TECHNOLOGICAL INNOVATIONS

While the basic technology of hydraulic fracking had been known long before its boom in the 2000's, the fracking of today has little in common with the processes used 15 years ago. Part of what spurred the rapid increase in hydraulic fracking efficiency was the ability of companies to specialize individual fractures to the unique geology of specific sites. The success of fracking is not the story of a single major innovation, but instead is the result of a gradual process with various new technologies being developed that, when combined and used in conjunction with one another, led to great cost efficiencies in production. Specifically, there were five key innovations that came together to spur the fracking boom: slick water fracking, 3-D seismic imaging, micro-seismic fracture mapping, synthetic diamond drill bits, and horizontal drilling. With the exception of slick water fracking, none of these technological innovations were new or revolutionary in the 2000s, but their combined use allowed hydraulic fracking to become highly customizable.

SLICK WATER FRACKING

Developed by Mitchell Energy for use in the Barnett Shale play, slick water fracking changed the industry standard on the composition of fracking fluid. Traditionally, fracking fluid was highly viscous and chemical based, such as nitrogen foams or gels. In contrast, the composition of slick water is primarily water, with small amounts of proppants, usually sand, and an even smaller amount of chemicals. Kent Bowker, of Star of Texas Energy Services, explained that slick water fractures "were a radical concept during this time because the general consensus among completion engineers was that as much proppant (sand) as economically possible had to be placed in the Barnett shale play in order to maximize fluid conductivity to the wellbore. Gel can carry plenty of proppant, un-gelled water can carry very little" (Bowker 2007). Though Mitchell Energy's initial slick water was 80% water and 20% sand, research and usage has shown that an even higher proportion of water is more effective. The use of small amounts of various chemical additives also increased production. Additives used can include biocides, acids, friction reducers, and surfactants to reduce the surface tension of the slick water. Though the exact recipe of each fracking company tends to be a trade secret, Figure 5 shows a hypothetical composition of slick water fracking fluid. Slick water fracking turned out to be a much better form of hydraulic fracking for certain shale formations, reducing the startup costs significantly. In shale gas formations, it was a major breakthrough—reducing the cost of releasing the resources by about 50 percent with similar initial production rates and higher subsequent production rates (Steward 2007).

FIGURE 5. HYPOTHETICAL SLICKWATER COMPOSITION



Source: Author's Concept

3-D SEISMIC IMAGING

ExxonMobil pioneered 3-D seismic imaging roughly 50 years ago to more accurately detect underground geologic formations when compared to traditional 2-D mapping. 3-D seismic imaging works by emitting acoustic reflections and recording how the geologic formations beneath the surface reflect the sound waves and providing details of formation, density, water pockets, etc. It provides a more accurate picture of the structure and properties of the subsurface geology. Prior to the 2000s, the cost of 3-D seismic imaging was prohibitive, and many companies opted to use the less detailed 2-D mapping. This technology was less reliable and made fracking economically infeasible for many sites. 3-D seismic imaging could give companies the information they needed to confidently drill, and when the costs of 3-D seismic imaging dropped, became the industry standard.

MICRO-SEISMIC FRACTURE MAPPING

While 3-D seismic imaging maps the underground geology, micro-seismic fracture mapping is a passive method that uses sensors to listen for underground seismic energy and record the minor seismic events generated during the fracturing of a nearby well. This technology can reveal the height, length, orientation, and other attributes of induced fractures, allowing companies to see increased details of their specific fracture. This information allows the operator to make informed decision about well stimulation to optimize resource extraction while minimizing costs.

SYNTHETIC DIAMOND DRILL BITS

For much of its early history, the most cost prohibitive factor in shale gas extraction was the physical act of well drilling. Because shale plays are located deep in the Earth's crust, effective hydraulic fractures needed to be anywhere from 5,000 to 20,000 feet deep. Compared to a standard oil well which generally does not exceed 5,000 feet in depth, drilling to access shale greatly increased costs. A major innovation in the 1970s that helped to alleviate drilling costs was the polycrystalline diamond compact (PDC) drill bit by General Electric. GE's process of diamond synthesis greatly reduced the costs associated with creating the materials needed for highly effective diamond drill bits. Their innovation allowed other companies, including Schlumberger, to experiment with different drill bit designs using the PDC material. The Society of Petroleum Engineers reported that "on a cost per foot basis, the PDC bits drilled these intervals at an average of 40% less than the roller-cone bits" (1985). Rather than crushing the stone as with a traditional (roller-cone) bit, the PDC bits sheared through the stone, reducing the amount of wear and tear damage each bit experienced. The combination of GE's material with innovations in bit design led the way for cost effective drilling that could be specialized for unconventional shale formations.

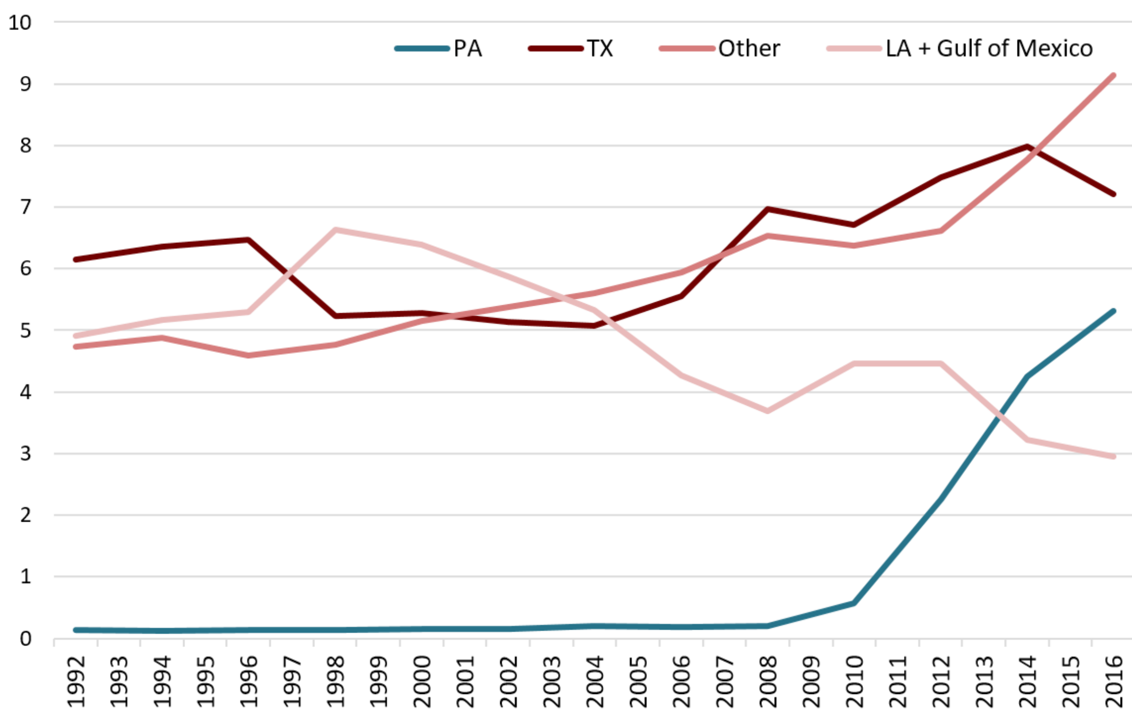
HORIZONTAL DRILLING

Traditionally, oil and gas wells were drilled straight down and drillers hoped to hit a reservoir of resources. Horizontal drilling involves drilling straight down for a mile or more, and then drilling horizontally. Though the technology to drill horizontally has existed for some time, it was generally not economically feasible since there was no way of knowing if the area around the well was worth drilling. It was not until Republic Energy used 3-D seismic imaging, in conjunction with micro-seismic fracture mapping, that horizontal drilling became feasible. Having the information provided by both kinds of mapping was essential to optimizing fracture placement and height (Steward 2007). It also makes a single well much more efficient, as it can drill branches off into many different directions: areas that once would have required 10 separate vertical wells can now be drilled by a single horizontal well.

RESULTS FOR SELECTED STATES

Hydraulic fracking has led the way for increased oil and gas production in the United States, although the benefits to individual states depends on geology and location. Oil and gas resources are closely tied to the location of shale plays across the country and the rise of hydraulic fracking has clearly benefited certain states more than others. In the case of natural gas, the increased use of hydraulic fracking has reduced the U.S.'s previous focus on offshore drilling, as companies focus more on the lucrative and cost-effective shale gas, such as the Barnett shale in Texas or the Marcellus shale in Pennsylvania. Figure 6 tracks the production in the highest producing states from 1990-2016.

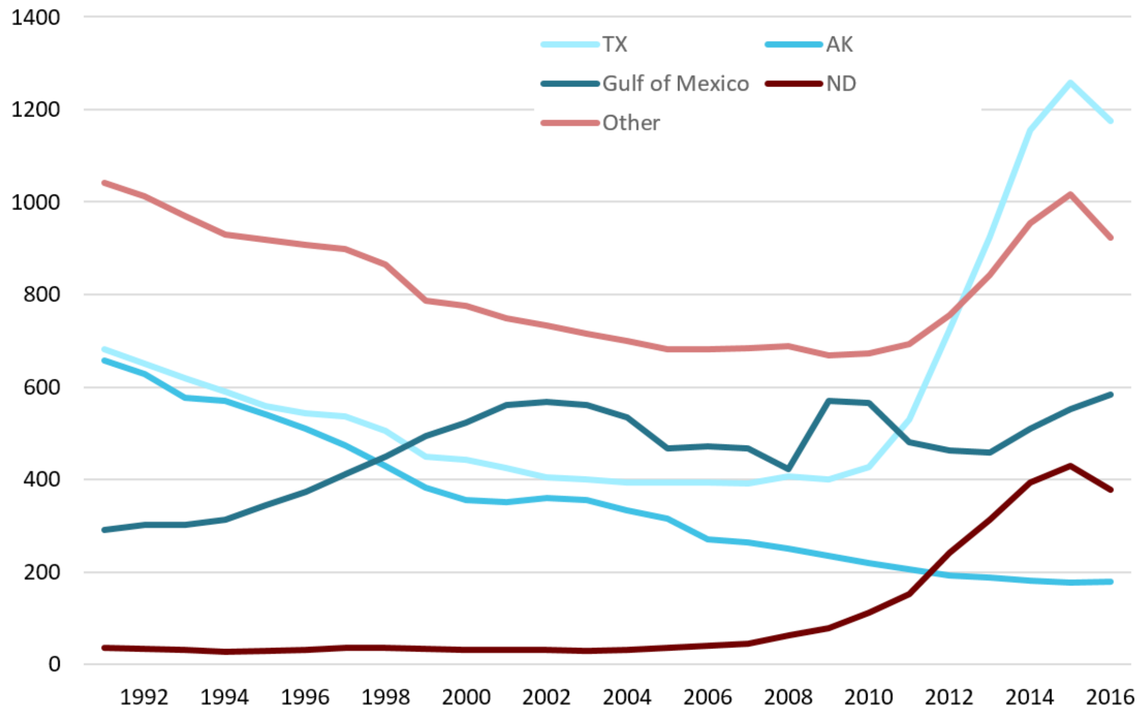
FIGURE 6. ANNUAL U.S. NATURAL GAS PRODUCTION BY STATE (trillion cubic feet)



Source: Energy Information Association: Natural Gas Gross Withdrawals and Production

Figure 6 illustrates how slick water fracking turned out to be a much better form of hydraulic fracking for certain shale formations, reducing the startup costs significantly. Texas shows a large rise in production since 2004, thanks in part to the Barnett and Eagle Ford shale play. Perhaps the most surprising states is Pennsylvania, with natural gas production rising from near zero in 2006 to an annual production exceeding 5 trillion cubic feet by 2016. Pennsylvania's natural gas production is centered on the Marcellus Shale play. There have been various small-scale fracking operations in smaller shale formations across the United States, reflected in the rising line labeled "Other." Louisiana, using offshore drilling, has seen large decreases in production as their gas has become less cost efficient relative to hydraulic fracking.

FIGURE 7. ANNUAL U.S. CRUDE OIL PRODUCTION BY STATE (millions of barrels)



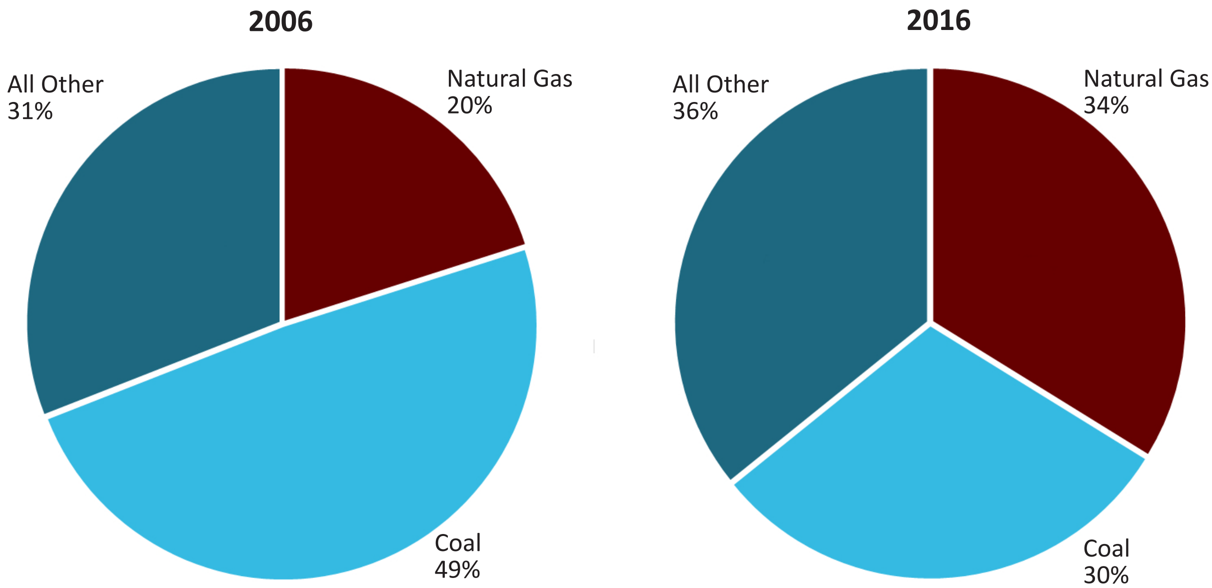
Source: Energy Information Association: Crude Oil Production

In the case of oil, the story is similar. Total production has increased, though to a lesser extent than natural gas. Figure 7 analyzes the highest producing states for crude oil from 1990 to 2016. Texas experienced the most drastic shift, increasing from 400 million barrels in 2009 to an all-time high of 1250 million barrels of oil in 2015, a 200% increase in just seven years. North Dakota's production increased from minimal levels before 2005 to 400 million barrels in 2015, thanks to the resources in the Bakken shale. On the other hand, Alaska has seen a steady decline in oil production since the 1990s.

Additionally, as the United States moves more towards natural gas as the fuel of choice for producing electricity, many have hailed this as the bridge to a low carbon future. Historically, the United States has produced most of its electricity from burning coal, releasing many tons of CO2 into the atmosphere. According to the Energy Information Association, each million Btu of electricity generated from coal produces anywhere from 214.3 to 228.6 pounds of CO2, depending on the type of coal used. The same amount of energy using natural gas releases 117 pounds of CO2, nearly a 50% decrease. Compared to coal, natural gas also produces fewer other emissions. For example, coal produces 5.26 pounds of sodium dioxide per megawatt hour, compared to 0.01 pounds per megawatt hour for natural gas. Coal produces 2.09 pounds of nitrogen oxide per megawatt hour compared to 0.37 pounds per megawatt hour for natural gas. Compared to natural gas, coal alsoproduces far more mercury and particulates. [1]

[1] Massetti et al (2017)

FIGURE 8. UNITED STATES ELECTRICITY BY SOURCE



Source: Energy Information Association: Electricity Data Browser

Figure 8 shows the distribution of electricity sources in 2006 and in 2016. The rise of hydraulic fracking led to the increased use of natural gas in electric power generation and a concurrent decrease in the use of coal. In 2016, natural gas overtook coal as the majority source of electricity in the U.S.

CONCERNS ABOUT FRACKING

Hydraulic fracking has raised a number of environmental and health concerns and the risks associated with its increased use are not fully known. Two frequently discussed areas of concern are increased seismic activities and water contamination.

INCREASED SEISMIC ACTIVITY

A commonly expressed concern associated with the use of hydraulic fracking is whether it may cause an increase in the number and severity of earthquakes. The United States Geological Society distinguishes between earthquakes caused by fracking and earthquakes caused by injection wells for wastewater disposal. In a USGS publication, Rubinstein and Mahani (2015) claim that, "in Oklahoma, which has the most induced earthquakes in the U.S., only 1-2% of the earthquakes can be linked to hydraulic fracturing operations. The remaining earthquakes are induced by wastewater disposal." 'Deep disposal of fluids' occurs in oil and gas operations of all types, not just hydraulic fracking. Canadian researchers Bao and Eaton found that in Alberta, Canada, "earthquake sequences exhibit clear spatial and temporal correlation with hydraulic fracturing" (2016), although a causal link was not identified. Both sets of researchers emphasize the need for more data to analyze the potential seismic risks from hydraulic fracking.

GROUNDWATER AND SURFACE WATER CONTAMINATION

Hydraulic fracking consists of pumping millions of gallons of fluid into the earth, leading to concerns that these hydraulic fluids will leak into drinking water aquifers and reservoirs. Fracking proppant include chemicals that are not suited for human consumption and have the potential to cause severe health problems. There are also concerns that gases that are released by fracking, such as methanol, may also contaminate drinking water sources. Because hydraulic fracking is a relatively recent phenomenon, there is limited research available on the risk of groundwater contamination, and the research that does exist is often contradictory and tends to be highly politicized.

On one side, George E. King lists multiple reasons why the risks of groundwater contamination are often overstated. He claims that in deep wells, the fracking does not travel through the rock far enough to harm water supplies, and a meta-analysis of "thousands of field-monitoring tests and millions of fracturing jobs have confirmed this point" (King 2012). He points out that even shallow horizontal wells are thousands of feet below the deepest freshwater sands, and he estimates that there is 3,000-5,000 feet separating the top of an average fracture and the bottom of a freshwater deposit. He adds that, to date, there have been no documented cases of any chemical contamination in water sands from hydraulic fracking. He concedes, however, that chemical contamination can occur from careless road transport and improper on-site storage. These are risks that could affect surface water, and are not intrinsic to hydraulic fracking per se, but to oil and gas operations in general. He argues that as long as wells are being drilled in line with standard practices, there is almost no risk of contamination of the surrounding groundwater. He argues that risks from improper storage and transport can be solved with stronger regulations, and that "the states with the fewest problems are those with strong state regulations" (King 2012).

Others are not so sanguine and claim that hydraulic fracturing is responsible for multiple cases of groundwater contamination. Patterson et al found that, "between 2005 and 2014 there were 6,648 spills reported across the four states… Our results exceed the number of spills found by EPA … because we included spills that occurred during all stages of unconventional production (from drilling through production) while the EPA focused on those spills explicitly related to hydraulic fracturing" (2017). The authors report that roughly 50% of leaks were related to transportation, which is somewhat in agreement with King.

One study, DiGiulio and Jackson (2016), reports contamination of a Wyoming aquifer, which the authors attribute to the leak of injected acid stimulation fluids into formations and to the use of unlined surface pits for disposal of production fluids prior to 1995.

In the 2016 abstract to "Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States," a major study released by the U.S. Environmental Protection Agency, the EPA concluded that while the "EPA found scientific evidence that hydraulic fracturing activities can impact drinking water resources under some circumstances," the EPA also found that "Data gaps and uncertainties limited EPA's ability to fully assess the potential impacts on drinking water resources locally and nationally. Because of these data gaps and uncertainties, it was not possible to fully characterize the severity of impacts, nor was it possible to calculate or estimate the national frequency of impacts on drinking water resources from activities in the hydraulic fracturing water cycle."

[2] Note how this illustrates one feature of the debate –- one side wants to attribute to fracking risks that arise from oil and gas operations that are not unique to fracking, while the other side wants to attribute to fracking only risks that arise strictly due to fracking, the 'marginal risk' of fracking instead of traditional production.
[3] Unlined surface pits for disposal of production fluids were emptied and closed in 1995.

CONCLUSION

In the past decade, hydraulic fracking has been at the forefront of the United States' massive energy boom. Its effect on America's energy independence cannot be overstated. It led to almost a 50% increase in American oil and gas production, an increase far beyond that of other resource-rich countries. To date, this has been a uniquely American phenomenon, as it has yet to fully take off in the rest of the world.

The story behind hydraulic fracking is the story of innovation and invention coming together to cause a change in the basic production processes used in one of our key industries. The rise of hydraulic fracking is a premier example of technological change and its effects on the U.S. economy.

Though research on the risks of hydraulic fracking are unclear, there is cause for vigilance and further study. One point that both sides agree on is the need for a stronger policy focus on proper transport, storage, construction, and disposal of waste products from oil and gas production.

The increased availability and use of natural gas has led to a shift away from coal as America's primary electricity source. Natural gas has been hailed as a gateway to a cleaner energy future and as a cheaper alternative to coal, and it seems that natural gas and the use of hydraulic fracking to acquire it are here to stay.

AUTHORS

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