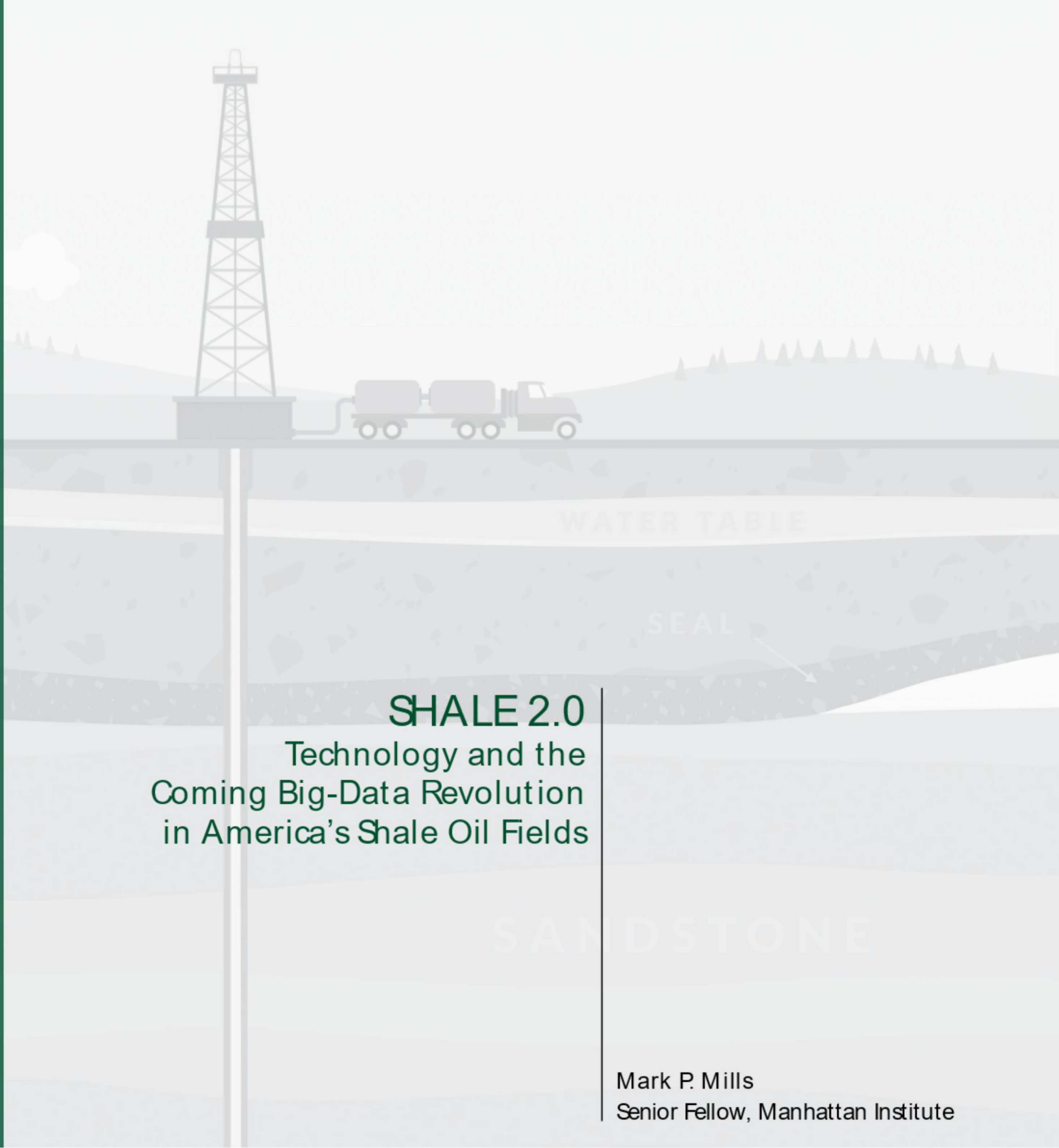
Energy Policy & the Environment Report



SHALE 2.0

Technology and the Coming Big-Data Revolution in America's Shale Oil Fields

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Executive Summary

With petroleum prices down 50 percent over the past year, many analysts and pundits are predicting the end of America's shale oil boom. Recent headlines include: "Oil Price Fall Forces North Dakota to Consider Austerity" (New York Times);[1] "Oil Price Drop Hurts Spending on Business Investments" (Wall Street Journal);[2] "The American Oil Boom Won't Last Long at $65 per Barrel" (Bloomberg Business);[3] and "The Shale Oil Revolution Is in Danger" (Fortune).[4]

High prices, shale skeptics argue, created a bubble of activity in unsustainably expensive shale fields. As shale-related businesses contract, consolidate, and adjust to the new price regime, a major shale bust is inevitable, they add, with ghost towns littering idle fields from Texas to North Dakota.

It is true that the oil-price collapse was caused by the astonishing, unexpected growth in U.S. shale output, responsible for three-fourths of new global oil supply since 2008. And as lower prices roil operators and investors, the shale skeptics' case may seem vindicated. But their history is false: the shale revolution, "Shale 1.0," was sparked not by high prices—it began when prices were at today's low levels—but by the invention of new technologies. Now, the skeptics' forecasts are likely to be as flawed as their history. This paper explains how continued technological progress, particularly in big-data analytics, has the U.S. shale industry poised for another, longer boom, a "Shale 2.0."

The End of the Beginning

John Shaw, chair of Harvard's Earth and Planetary Sciences Department, recently observed: "It's fair to say we're not at the end of this [shale] era, we're at the very beginning."[5] He is precisely correct. In recent years, the technology deployed in America's shale fields has advanced more rapidly than in any other segment of the energy industry. Shale 2.0 promises to ultimately yield break-even costs of $5–$20 per barrel—in the same range as Saudi Arabia's vaunted low-cost fields.

The shale industry is unlike any other conventional hydrocarbon or alternative energy sector, in that it shares a growth trajectory far more similar to that of Silicon Valley's tech firms. In less than a decade, U.S. shale oil revenues have soared, from nearly zero to more than $70 billion annually (even after accounting for the recent price plunge). Such growth is 600 percent greater than that experienced by America's heavily subsidized solar industry over the same period.[6]

Shale's spectacular rise is also generating massive quantities of data: the $600 billion[7] in U.S. shale infrastructure investments and the nearly 2,000 million well-feet drilled have produced hundreds of petabytes of relevant data. This vast, diverse shale data domain—comparable in scale with the global digital health care data domain—remains largely untapped and is ripe to be mined by emerging big-data analytics.

Shale 2.0 will thus be data-driven. It will be centered in the United States. And it will be one in which entrepreneurs, especially those skilled in analytics, will create vast wealth and further disrupt oil geopolitics. The transition to Shale 2.0 will take the following steps:

1. Oil from Shale 1.0 will be sold from the oversupply currently filling up storage tanks.
2. More oil will be unleashed from the surplus of shale wells already drilled but not in production.
3. Companies will "high-grade" shale assets, replacing older techniques with the newest, most productive technologies in the richest parts of the fields.

About the Author

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Mills is a contributor to Forbes.com and is coauthor of The Bottomless Well: The Twilight of Fuel, the Virtue of Waste, and Why We Will Never Run Out of Energy (Basic Books, 2005), which rose to #1 on Amazon's science and math rankings. His articles have been published in various popular outlets, including the Wall Street Journal and New York Times Magazine. Mills is also a frequent guest on CNN, FOX, NBC, and PBS, and has appeared on The Daily Show with Jon Stewart.

Earlier, Mills was a technology adviser for Bank of America Securities, and a coauthor of a successful energy-tech investment newsletter, the Huber-Mills Digital Power Report. He has testified before Congress and has briefed many state public service commissions and legislators. Mills served in the White House Science Office under President Reagan, and subsequently provided science and technology policy counsel to numerous private sector firms, the Department of Energy, and U.S. research laboratories.

Early in his career, Mills was an experimental physicist and development engineer, working at Bell Northern Research (Canada's Bell Labs) and the RCA David Sarnoff Research Center on microprocessors, fiber optics, missile guidance, nuclear energy, and non-proliferation. He earned several patents for his work in these fields. Mills holds a degree in physics from Queen's University, Canada.

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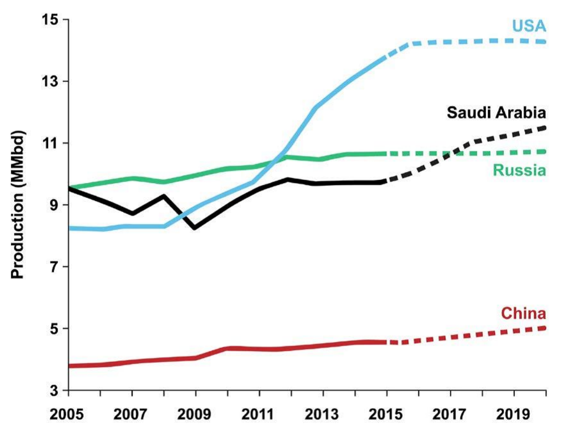
INTRODUCTION

In 2014, America's oil production grew by 1.2 million barrels per day (MMbd)—the greatest single-year increase since the oil age began more than a century ago.[8] Over the past half-dozen years, U.S. oil output rose by a total of 4 MMbd, with most of the growth in the past three years (Figure 1).

The invention by American entrepreneurs of a new way to manufacture oil from shale, at volumes and prices that have moved global markets, has been the biggest disruption to the energy landscape in 30 years. If the U.S. shale industry alone were a country, it would rank as the world's fifth-largest hydrocarbon producer.

The last time so much oil was added in such a short period to world markets was in 1986, when Saudi Arabia—which then enjoyed far greater spare capacity than it now does[9]—made a strategic decision to increase output by 3 MMbd. That flood of oil drove global prices down to $20 per barrel (2014 USD). This time, the plunge in prices was caused not by a foreign oil monarchy but by thousands of American entrepreneurs drilling on state and private lands.

Figure 1. U.S. Shale Production Changed the Global Oil Landscape*



* Includes natural gas liquids for all countries
Data Source: EIA

deployment of new technologies that enabled the economic production of oil from shale.

Although America's shale industry is new, its scale is such that it is now a permanent fixture of the U.S. techno-industrial base. The U.S. shale ecosystem has exploded—from essentially nonexistent, just over a decade ago—to a $300 billion component of GDP, featuring thousands of companies. The U.S. shale ecosystem is also a distinctly different industry, in structure, operation, and technique, compared with its cousin, the conventional hydrocarbon industry.

But the price collapse has started to affect U.S. shale oil production. In January 2015, output trended down, by 0.12 MMbd, compared with the previous month, for the first time since 2010. Lower prices mean that certain shale companies with weak financials will end up being acquired, while others will go bust.[10]

$65 per Barrel" (Bloomberg Business);[13] "The Shale Oil Revolution Is in Danger" (Fortune);[14] and "United States Will Not Become the 'New Saudi Arabia' of Global Energy" (Telegraph).[15]

What if—absent exogenous events such as major wars and short-term price oscillations—oil never again sells for much more than $60 per barrel for decades? This is a real possibility in a world consistently fully or episodically oversupplied with oil, especially if U.S. shale output continues. But can America's shale industry survive?

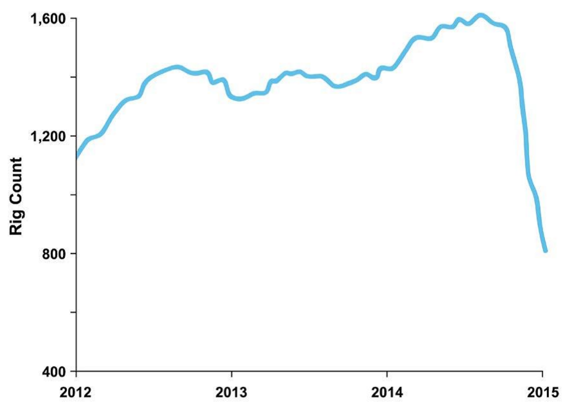
In fact, in the roughly 150-year history of oil prices, there have been just three short periods where oil sold for more than (inflation-adjusted) $50 per barrel (Figure 2). Yet over the same period, technological progress has enabled world oil production to soar by 6,500 percent.

But the recent plunge in oil prices has caused a precipitous drop in the use of U.S. drilling rigs (Figure 3). With the rig count the easiest, most widely publicized, measure of activity in the oil and gas industry, numerous media reports and pundits now argue that this is an ominous indicator of future oil output.

But the rig count alone is not a reliable indicator of what the future holds. The shale business is as

Figure 2. Oil Prices, 1861–2014

Figure 3. U.S. Oil Rig Count



Data Source: Baker Hughes

different from its predecessor, conventional oil and gas, as the smartphone ecosystem is different from telephony. And just as the smartphone ecosystem is new and rapidly evolving, so, too, is the industrial ecosystem of shale hydrocarbons.

In the end, shale technology, as with any technology, is only useful if it can deliver the goods at ever-decreasing cost. Thus the central questions for analysts and investors about the future of America's young shale industry are: Where is the technology going? Can more oil be unlocked at lower costs and with fewer rigs?[16]

I. TECHNOLOGY: THE EPICENTER OF A NEW INDUSTRY

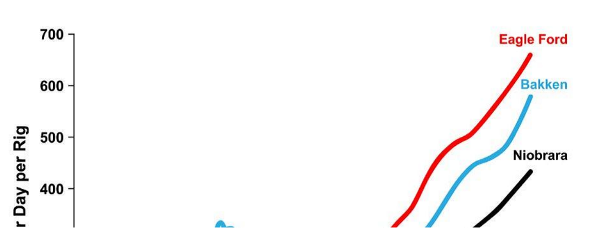
The price and availability of oil (and natural gas) are determined by three interlocking variables: politics, money, and technology. Hydrocarbons have existed in enormous quantities for millennia across the

While the conventional and so-called unconventional (i.e., shale) oil industries display clear similarities in basic mechanics and operations—drills, pipes, and pumps—most of the conventional equipment, methods, and materials were not designed or optimized for the new techniques and challenges needed in shale. By innovatively applying old and new technologies, shale operators propelled a stunningly fast gain in the productivity of shale rigs (Figure 4), with costs per rig stable or declining.

Shale companies now produce more oil with two rigs than they did just a few years ago with three rigs, sometimes even spending less overall.[17] At $55 per barrel, at least one of the big players in the Texas Eagle Ford shale reports a 70 percent financial rate of return.[18] If world prices rise slightly, to $65 per barrel, some of the more efficient shale oil operators today would enjoy a higher rate of return than when oil stood at $95 per barrel in 2012.[19]

Extracting hydrocarbons from shale is fundamentally different from extracting hydrocarbons from conventional wells. The former requires two distinct steps: (1) after drilling down vertically, 5,000–10,000 feet, to reach a shale formation, operators drill long, 5,000–10,000-foot horizontal wells; (2) hydraulic pressure is then used to fracture the rock ("frack"), releasing oil and gas.

Figure 4. Average Oil Production per Shale Well, Four Major Shale Fields, 2007–15



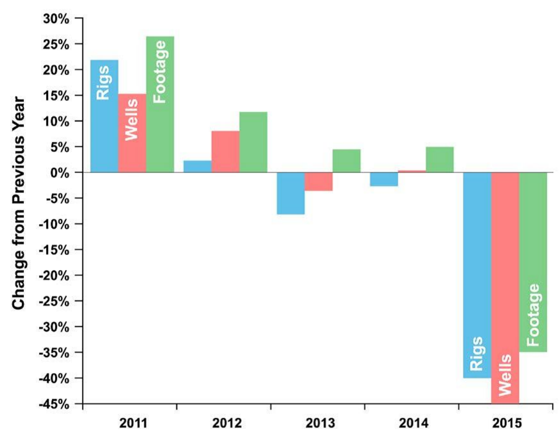
The time it takes to drill wells is a critical component of cost. On this front, the speed of improvement has been remarkable: with virtually no increase in capital costs (in some cases, costs are down),[20] the three key measures of drilling—time to drill, wells per rig, and total distance drilled—have improved by 50–150 percent in less than five years (Figure 5).

The number of feet of shale rock tapped is the first-order determinant of how much oil and gas are produced. Here, the net result of technology and operational innovation is clearly visible: total footage drilled grows faster than the growth in rig count (Figure 6). The inverse is true as well: a forecasted 40 percent drop in rig count will have a more modest (35 percent) decline in total new footage drilled.

The "walking rig" is one technological advance that has contributed greatly to gains in rig productivity. Rather than drill a single well from a well-pad, a walking rig can move around the pad, drilling multiple wells (sometimes dozens) (Figure 7).[21] Since 2006, the use of such so-called pad drilling has grown dramatically, from a few percent to over 50 percent of new wells, with the potential to rise higher.[22]

The use of older, less efficient "Generation 1" (Gen 1) and "Generation 2" (Gen 2) rigs began declining in 2011, long before the late 2014 overall rig falloff. (As of the first quarter of 2015, the number of Gen 1 rigs was down by 60 percent from peak use.) During 2011 to late 2014, as Gen 1 and Gen 2 rig use declined, the number of newer, faster, more powerful "Generation 3" (Gen 3) rigs rose by 60 percent. Even now, the number of Gen 3 rigs is down by only 25 percent, compared with the deeper overall plunge in Gen 1 and Gen 2 rigs (Figure 8).[23]

Figure 6. Technology Causes Rig Count to Disconnect from Well-Feet Drilled



Data Source: Drilling Contractor; and Spears & Associates, "Drilling Market Outlook"

Figure 5. Shale Rig Drilling Efficacy, Typical Four-Year Changes

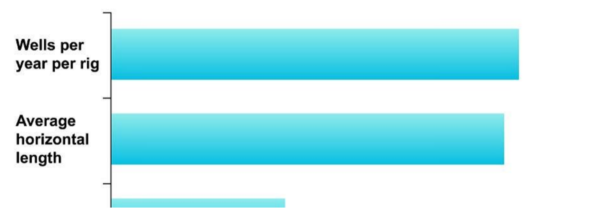
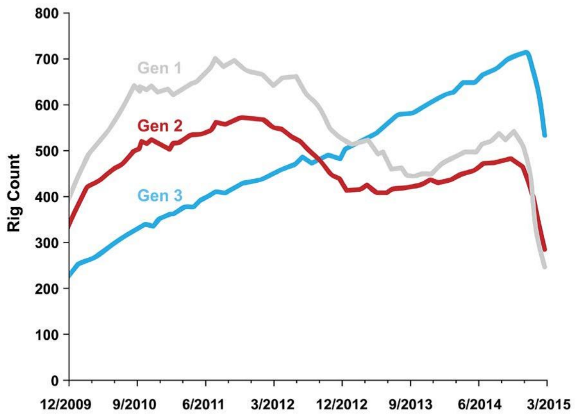


Figure 7. Drilling Multiple Wells from a Walking Rig

Figure 8. Rig Count by Type of Technology



Data Source: Helmerich & Payne

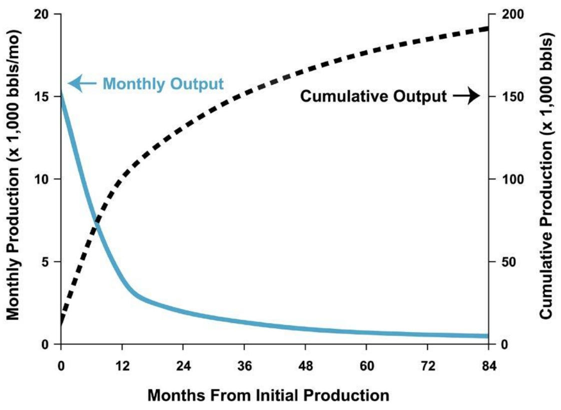
Once a well is drilled and 1–2 miles of horizontal pipe placed in the shale, the key factor that determines the well's value is the effectiveness of the completion step (i.e., when hydrocarbon-bearing rock is stimulated to produce oil and gas). Spending on completion typically accounts for 50–60 percent of the total development cost of shale wells.[24] Here, too, productivity gains have been remarkable, with a 400 percent rise in output during a well's first month of operation; even two to three years into production, technological advances have boosted output by 200 percent in just a few years.[25]

While all oil and gas wells deplete as they produce, shale wells do so at a faster rate than conventional wells. Half of a shale well's lifetime output typically occurs in the first year and 75 percent during its first three years—investors thus enjoy a very fast return on capital. But a well's cumulative production continues to rise over time. In a typical shale field, because shale

motors, and better cementing and perforating of pipe.[26] Operators, for example, increasingly use more powerful pumps to move the water-sand mixture faster and at higher pressures, greatly increasing the amount of sand used to keep shale cracks open (Figure 11).

Sand used per well has risen, from 5 million to 15 million pounds, on average; the additional sand adds 2 percent to completion costs but boosts output by 40 percent.[27] A typical shale well, which involves a

Figure 9. Monthly vs. Cumulative Output for Typical Shale Well



Data Source: The Oil Drum

Figure 10. Rig Count vs. Total Output in Representative Shale Field

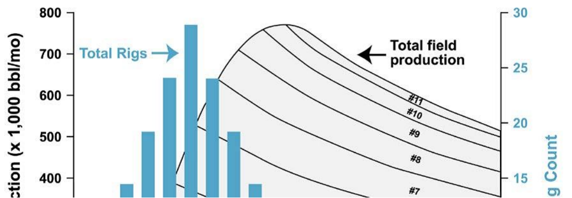


Figure 11. Sand Delivery and Logistics*

* Custom-designed truck converts into sand silo.
Source: Halliburton

bewildering array of pipes, pumps, motors, valves, gauges, engines, tanks, trucks, and people—most onsite only temporarily—truly represents "a study in mechanical excellence."[28]

II. RIG COUNT VS. OUTPUT

With rig counts down but rig productivity soaring, what next? The consequences of a price and rig-count collapse have played out before. The shale revolution, in fact, began with the extraction of natural gas in the Texas Barnett shale. In 2008, after natural gas from this abundant new source flooded the U.S. market, gas prices plunged threefold. The gas rig count fell; but gas production kept rising and has been growing ever since.[29] Figure 12 illustrates the effect of radical gains in rig productivity for shale gas.[30]

As for oil, the impact of rising shale-rig technologies, oil sold for less than $50 per barrel; when production first took off, the price was still below $60 per barrel.

III. TECHNOLOGY HIGH-GRADING, THEN SHALE 2.0

Four developments will likely determine the future supply of shale oil:

- Oil will be sold from the oversupply currently placed in storage tanks.
- Operators will more efficiently unleash oil from wells drilled but not completed.
- Operators will swiftly adopt the best new technologies and use them in the best parts of the shale ("high-grade assets").
- Operators will embrace big-data analytics, unleashing Shale 2.0—greater production at lower cost.

Peak Storage

The total quantity of American petroleum now parked in huge steel tanks is at levels not seen for 80 years. A decade ago, no one thought that the U.S. would experience challenges associated with "peak storage," rather than "peak oil." In February 2015, one massive oil

Figure 12. Natural Gas: Fewer Rigs, Far More Output

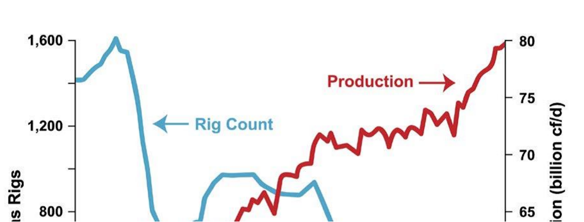
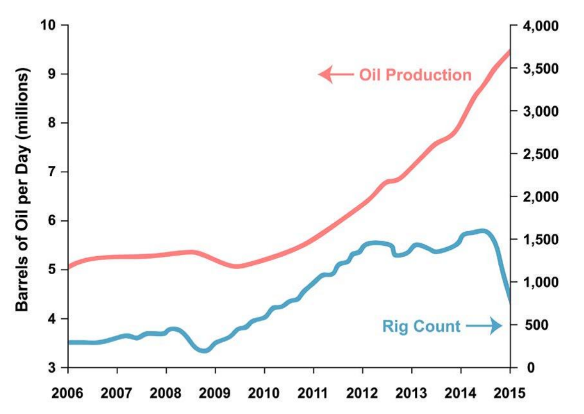


Figure 13. Petroleum:
Shale Production vs. Rig Count



Data Source: EIA and Baker Hughes

storage farm, in Cushing, Oklahoma, was 75 percent full; in February 2014, it was 48 percent full.[31]

The current oil storage glut is mainly a consequence of two factors: inadequate infrastructure and misguided law. American oil transport infrastructure, both pipelines and railroads, is still catching up to the recent, radical increase in domestic production. But even if the necessary infrastructure existed, half-century-old federal rules prohibit American companies from selling crude oil internationally—despite the fact that it is legal to sell refined oil (gasoline, diesel, aviation fuel) overseas. This outdated statute not only inhibits private investment in export infrastructure; it also violates the basic market principles that guide U.S. export policy for nearly all other products.[32]

Still, it is unlikely that this law will soon be replaced or that new export infrastructure will be

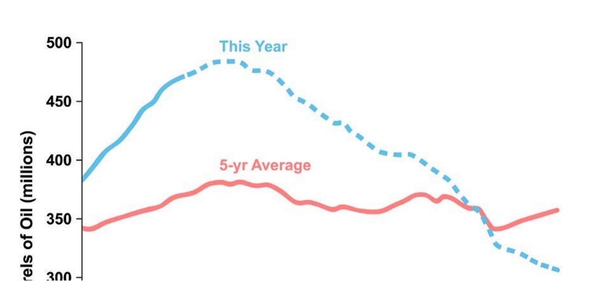
growth (and, accordingly, lower incomes). If oil in storage returns to recent average storage levels (Figure 14), nearly a million barrels of oil per day could enter the market.

The Fracking Backlog

Even more oil supply is now, de facto, being stored underground. As noted, production begins with the distinct second stage of well construction. Once a shale site is mapped and long horizontal wells completed, operators can delay the expensive step of fracking. Since the latter constitutes 50–60 percent of total costs, significant spending can be deferred with no loss of the core asset. The oil is simply left stored, in situ, until markets and prices make retrieval more attractive. When such sites are eventually stimulated, operators will be able to harness technological advancements that have occurred in the interim.

The U.S. currently has roughly 3,000 drilled wells awaiting completion—likely rising by the end of 2015, to more than 5,000.[34] Given current market realities, many—if not most—such wells will remain idle.[35] The amount of ready-to-flow oil stored in those 5,000 wells is at least four times greater than

Figure 14. Oil in Storage*



all the oil stored in steel tanks around the country. Because it takes only a few months to complete a well, such wells, once completed, could swiftly add 2–3 MMbd to U.S. supply.

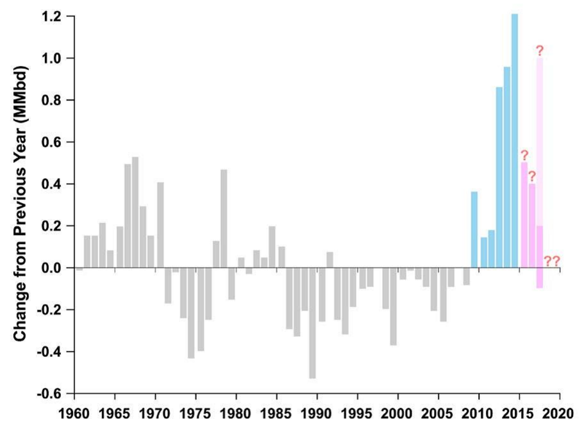
Embracing Technology

As operators gained experience during the first shale boom, Shale 1.0, a popular strategy involved duplicating every aspect of the development of a successful well on successive wells within the same field. This repetitive, “factory drilling” strategy made sense during the industry’s expansion because it eliminated the risks associated with continued experimentation. And when factory drilling in new parts of the same field yielded poorer results, due to variations in shale geology, the (coincidental) surge in oil prices reduced the incentive to innovate. (When oil hovered at $100/barrel, a factory-drilled well that was 30–50 percent less productive than previous factory-drilled wells was still a big moneymaker.)

In the new low-price oil environment, however, operators will increasingly—and soon, exclusively—adopt a high-grading strategy that the industry’s top performers have pursued for years. High-grading calls for operators to use analysis not only to modify techniques for each well but also to use the best tools and techniques in only the best parts of the shale. One implication of high-grading is that conventional forecasts for future supply likely represent underestimates because they are based on historical averages that incorporate the previous proliferation of low-performing wells drilled during the price boom.[36]

The effect of so many wells and acres subjected to high-grading will be to maintain output even

Figure 15. U.S. Oil Production, Past and Forecast



Data Source: EIA; and Spears & Associates

IV. BIG-DATA ANALYTICS WILL MAKE SHALE OIL CHEAPER

Incremental and dramatic improvements will continue in all aspects of the many technologies used in shale production: logistics, planning, seismic imaging, well-spacing, fluid and sand handling, chemistry, drilling speed, pumping efficiency, instrumentation, sensors, and high-power lasers.[38] Shale fields will increasingly be developed using advanced automation, mobile computing, robotics, and industrial drones. At present, barely 10 percent of projects use fully automated drilling and pressure-control systems, for example.[39]

Largely because of the tremendous scale of investment already in place, there is every reason to believe that such improvements—which portend greater and cheaper American oil production—will collectively be at least as significant in the coming

In every sector of the U.S. economy, the availability and collection of data from machines, services, and business operations are growing at an astonishing rate. Still, a large amount of the data remains disparate and disordered. The use of big-data analytics offers nearly all industries the potential for unprecedented insight, efficiency, and economic value. America's shale industry is similar to many other large, complex businesses—such as aviation, agriculture, manufacturing, entertainment, and health care—in the scale and diversity of its operations. What distinguishes shale is its unique combination of youth, the diversity and scale of data associated with its operations, and the variety of environments in which operations occur.

While such challenges could delay the industry's embrace of big-data analytics, the opportunity in oil and gas has not escaped the attention of IT firms such as IBM, Microsoft, Accenture, Cisco, and SAP, as well as various hydrocarbon-service companies. Conferences and books dedicated to the new specialty are rapidly appearing, including a new professional society focused on data-driven petroleum analytics.[41] The CEO of EOG, a shale firm founded in 1999 and now with $18 billion in revenue, promotes his company's aggressive, proprietary use of big data.[42] ConocoPhillips, founded in the nineteenth century and now with revenues of $55 billion, was ranked Number Two on InformationWeek's 2013 list of the 500 top IT-using firms.[43]

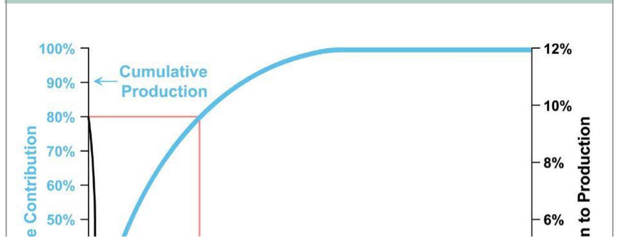
Big-data analytics can already optimize the subsurface mapping of the best drilling locations; indicate how and where to steer the drill bit; determine, section by section, the best way to stimulate the shale; and ensure precise truck and rail operations. Mobile computing, using app-centric analytics, can increase uptime, reduce maintenance, improve workforce productivity, reduce errors and rework, and enable

Schlumberger announced a 50 percent gain in production, thanks to its use of analytics.[46] ConocoPhillips combined the latest sensors (which extract data by the minute rather than daily), wireless networks (often requiring building dedicated remote cell and Wi-Fi towers), and big-data analytics to boost output by 30 percent in existing wells.[47]

Given such results and current low oil prices, it is little wonder that Baker Hughes, for instance, received more inquiries about its big-data analytics in the first quarter of 2015 than in the previous two years combined.[48] This confluence of technological maturity and market opportunity is ideally aligned for the upcoming pivot to data-centric Shale 2.0. Big-data analytics has also arrived at a time when demand and supply are well aligned: global demand for oil continues to rise, while America's shale fields are generating vast new supply.

Perhaps the most portentous indicator of the near-term opportunity for big-data analytics to yield more oil at lower cost is the surprisingly ineffective current mechanisms for stimulating shale to yield oil or gas (Figure 16). At present, each long horizontal well is typically stimulated in 24–36 stages, with, on average, only one-fourth to one-third of those stages productive.[49] At present, in other words, about 20 percent of stages generate 80 percent of output.

Figure 16. Effectiveness of Frack Stages in Horizontal Wells



The current state of stimulation technology means that, on average, at least 300–400 percent more oil is not extracted. Bringing analytics to bear on the complexities of shale geology, geophysics, stimulation, and operations to optimize the production process would potentially double the number of effective stages—thereby doubling output per well and cutting the cost of oil in half.

At present, break-even costs across U.S. shale fields range from $10 per barrel–$55 per barrel.[50] Delivering North Dakota oil to Gulf Coast refineries and ports by rail can add another $15 per barrel. Using analytics to double output, thus cutting oil costs in half, means that shale break-even costs would drop to $5 per barrel–$25 per barrel. America's shale fields would then be competitive in volume and in price with Saudi Arabia's vaunted ultralow-cost oil fields.

V. $100 OIL SET THE STAGE FOR SHALE 2.0

That world oil prices reached $100 per barrel in tandem with the expansion of the shale revolution accelerated the appetite of financial markets to invest in shale wells. The result: extraordinarily rapid expansion of the industry's physical and knowledge assets.

One indicator of just how much shale-related data have been generated is found in the hundreds of billions of dollars invested in data-generating hardware, infrastructure, and equipment. Another indicator of the scale of this new data set is the total distance of horizontal well-feet drilled. Ten years ago, only a handful of horizontal wells in shale formations existed. Two billion feet—enough to circle the earth more than 25 times—have since been drilled horizontally (Figure 17), in hundreds of thousands of wells in U.S. shale fields.[51]

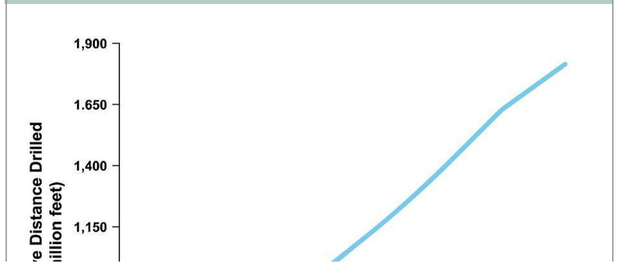
equipment, too. For example, a total of about 15 million horsepower in powerful diesel-driven pressure pumps are used to stimulate shale.[54] Few industries deploy so much engine power—it is more horsepower than used by FedEx's global fleet of trucks and rivals that used by Delta's entire aircraft fleet.[55]

In general, data are associated with and often collected for every foot of well drilled and operated, including: for the seismic subsurface maps; for the sensors used to analyze the earth during drilling; for the trains and trucks carrying sand and equipment to the site; for the pumps and flow meters pushing sand and water underground; for the hardware and software moving the product to market; and for safety and environmental compliance–related equipment. Spread across disconnected operational silos and different companies, there is likely (no one yet tracks it) on the order of 600 petabytes of data—there are, for comparison, about 500 petabytes of global digital health care data[56]—associated with finding, stimulating, extracting, and moving shale hydrocarbons.[57]

VI. BIG DATA IS THE NEW OIL

"Data is the new oil!" became a popular metaphor in the big-data analytics community.[58] Big-data analytics, it turns out, can also unlock oil itself.

Figure 17. Cumulative Distance Drilled in Horizontal Shale Wells*

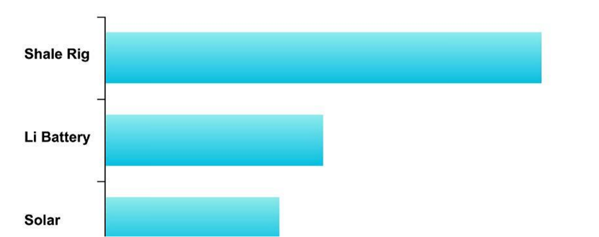


In 2011, Bill Gates predicted as much: "The one thing that is different today [in energy] is software, which changes the game."[59] Continuous innovation in materials sciences, basic engineering, and analytics is having a greater impact on oil and gas cost-effectiveness than on solar, wind, and battery technology (Figure 18), despite the fact that the latter are popularly viewed as epicenters of energy innovation.

In terms of energy output, per unit of capital cost, for energy-producing hardware, shale technology has improved by some 500 percent during the past five years;[60] wind turbines, solar cells, and lithium batteries have improved as well, but far less spectacularly.[61] Further, efficiency gains in alternative-energy technologies are slowing,[62] while shale technology shows few signs of a slowdown. Such trends refute the belief that tech progress is bypassing hydrocarbons.

The potential of big data is making analytics among the fastest-growing job categories in all industries, including hydrocarbons.[63] This will make it difficult for oil and gas firms to recruit such talent,[64] forcing shale firms to increasingly purchase services and tools directly from analytic-centric tech firms (such as Teradata, Splunk, Qlik, Palantir, and TIBCO Spotfire) and from hydrocarbon-centric tech companies (including FracKnowledge, NEOS GeoSolutions, Blade Energy Partners, and Austin-based Ayata). All will seek to mine the rich, often untapped data available in the thousands of connected sectors that constitute America's shale industry.

Figure 18. Efficiency Gains:
Shale Tech vs. Alternative Energy



Physical scale and enormous capital resources are critical for firms engaged in conventional hydrocarbons. Shale fields, on the other hand, are friendlier to start-ups and other small companies because of sharply lower capital costs and scale; ease of access to domestic (often private) land; and domestic infrastructure. Such advantages are now magnified by better sensors, communications, and inexpensive cloud-based supercomputing—a boon for the thousands of small and midsize American oil and gas companies that pioneered the Shale 1.0 revolution.

With data-driven productivity and automation leading Shale 2.0, we will see more jobs, not fewer. During Shale 1.0, as productivity soared, the number of workers per rig remained roughly constant, but the total number of people employed, directly and indirectly, in the shale ecosystem expanded. Indeed, in the six years following the Great Recession, America's shale sector led the country in job creation.[65]

As the industry adjusts to lower prices, slowing investment, and rising consolidation, however, layoffs are inevitable before the next expansion can begin. U.S. shale oil and gas is now, after software, the largest target for private-equity buyouts.[66] Much of this activity is below the public radar, though private-equity titans Blackstone and Carlyle have made headlines by launching multi-billion-dollar funds dedicated to the sector.[67] The

VII. THE STRUCTURE OF TECHNOLOGICAL REVOLUTIONS

America's young shale industry is following a well-established historical pattern for technological revolutions. When innovation spawns entirely new industries, from the car to the cell phone, the scale and impact of the technology, as well as the associated businesses deploying and using it, expand in two broad phases. The first involves an initial boom, when new products and production ramp up and experience is gained by trial and error. The second, significantly larger, boom arrives later—sometimes proceeded by a bust—spurred by experience and continued innovation.

The automobile era progressed from phase one in 1914, year of the first mass-produced cars, to phase two in the early 1950s, with the dominance of low-cost auto-making and associated infrastructure (national highways). The computer industry went from phase one in 1955, year of the first commercially deployed mainframes, to phase two in 1984, year of the first mass-produced personal computers. The cell phone advanced from phase one in 1990, with the first affordable phones, to phase two in 2007, with the introduction of smartphones and associated high-speed infrastructure.

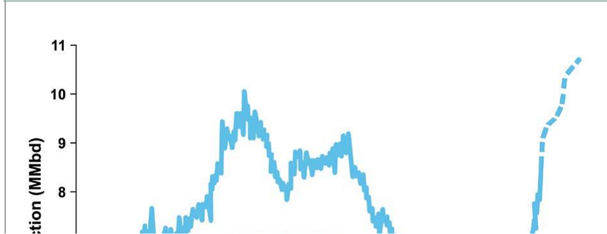
The history of conventional oil started in 1858, with Edwin Drake's 69-foot well in Titusville, Pennsylvania. Drake used a steam engine and salt-well drill, but his breakthrough involved placing iron pipes into the ground to keep the well bore open and drilling inside the pipes. The innovation was quickly copied, and an industry was born. Yet early drills could only make several feet of progress per day; so wells were shal-

Unconventional oil is set to follow a similar trajectory. Phase one started in 1991 in Texas's Barnett shale, when George Mitchell combined a subsurface seismic map, horizontal drilling, and hydraulic fracturing to stimulate rock to release hydrocarbons. In the process, Mitchell Energy (now part of Devon Energy) unleashed a shale boom similar in scale and character to the first oil era, and similar to previous industrial cycles. Twenty-five years later, history now awaits the name of the person or company that will be identified with launching Shale 2.0. In the meantime, shale's position as an enduring and soon-to-be $100 billion/year U.S. industry is secure (Figure 19).

CONCLUSION

In recent decades, developed nations have spent hundreds of billions of government dollars trying, and failing, to invent a cost-effective replacement for petroleum. Yet without taxpayer largesse, American entrepreneurs invented a new method to extract astounding quantities of oil from rock, upending the global hydrocarbon trade in the process. In a world where oil still powers 95 percent of air and ground miles and will remain dominant for decades, this represents a very positive development.[69]

Figure 19. U.S. Crude Oil Production, Post–World War II



Compared with 1986—the last time the world was oversupplied with oil—there are now 2 billion more people living on earth, the world economy is $30 trillion bigger, and 30 million more barrels of oil are consumed daily.[70] The current 33 billion-barrel annual global appetite for crude will undoubtedly rise in coming decades. Considering that fluctuations in supply of 1–2 MMbd can swing global oil prices,[71] the infusion of 4 MMbd from U.S. shale did to petroleum prices precisely what would be expected in cyclical markets with huge underlying productive capacity.

While sellers naturally prefer higher prices, the dramatic recent oil-price slump has set the stage for America's upcoming Shale 2.0 revolution. Given petroleum's continued economic and geopolitical importance, what policies should the U.S. pursue to maximize the benefits that it secures from Shale 2.0?

Legislators have yet to recognize and incorporate into law the far-reaching implications of how the energy landscape has fundamentally changed. U.S. energy law remains anchored in the decades-old paradigm of insatiable U.S. demand and resource shortages. The modern reality has instead utterly reversed, with de minimis growth in U.S. oil demand, exploding global demand, and an ascendant second era of American petroleum production. Congress should thus undertake a comprehensive review and rewrite of the 1974 Energy Policy & Conservation Act, which enshrined the now-antiquated paradigm. In the meantime, Congress can:

1. Remove counterproductive rules prohibiting U.S. companies from selling crude oil overseas, as well as rules inhibiting similar shale gas sales.
2. Remove the 1920 Merchant Marine Act's constraints on transporting domestic hydrocarbons by ship. This will require finding a more cost-effective solution to the national security interests associated with subsidizing a domestic shipbuilding industry.
3. Avoid inflicting further regulatory burdens on the already heavily regulated shale industry. Ominously, the U.S. Bureau of Land Management has announced plans for new standards that will affect about one-fifth of shale-based hydrocarbon production.[72]
4. Open up and accelerate access to exploration and production on federally controlled lands. This would boost domestic economic opportunities and send a powerful message about America's oil export ambitions—rivaling, in inverse, the announcement of the 1973 Arab oil embargo.

Further, while Congress works to unshackle a shale industry adjusting to lower prices, hydrocarbon firms might consider launching a "Shale Ready Vets" program—a private alternative to President Obama's new Solar Ready Vets[73]—offering instruction in vital, high-paying shale-related jobs, from machinery and supply-chain logistics to big-data analytics. At a time of growing scarcity for skilled labor in such fields, such a program would help prepare the U.S. workforce for the emergence of Shale 2.0.

Endnotes

1. “Oil Price Fall Forces North Dakota to Consider Austerity,” New York Times, AP, March 24, 2015, http://www.nytimes.com/aponline/2015/03/24/us/ap-us-xgr-slipping-oil-rigs.html.
2. Nick Timiraos, “Oil Price Drop Hurts Spending on Business Investments,” Wall Street Journal, March 22, 2015, http://www.wsj.com/articles/oil-price-drop-hurts-spending-on-business-investments-1427058389.
3. Matthew Philips, “The American Oil Boom Won’t Last Long at $65 per Barrel,” Bloomberg, December 1, 2014, http://www.bloomberg.com/bw/articles/2014-12-01/can-the-us-fracking-boom-survive-with-oil-65-per-barrel.
4. Shawn Tully, “The Shale Oil Revolution Is in Danger,” January 9, 2015, http://fortune.com/2015/01/09/oil-prices-shale-fracking.
5. Quoted in Alvin Powell, “Staying Power for Shale Gas: Geologist Sees a Path to Easing Fracking Concerns,” Harvard Gazette, March 12, 2015, http://news.harvard.edu/gazette/story/2015/03/staying-power-for-shale-gas/?utm_source=SilverpopMailing&utm_medium=email&utm_campaign=03.13.2015%20(1.
6. Solar Energy Industries Association, “Solar Market Insight Report 2014,” http://www.seia.org/research-resources/solar-market-insight-report-2014-q4; 2014 6 GW sales, of which 4 GW is utility scale @$2/W for primary energy-producing hardware.
7. See http://www.api.org/~/media/Files/Policy/SOAE-2014/API-Infrastructure-Investment-Study.pdf.
8. EIA, “US Oil Production Growth in 2014 Was Largest in More than 100 Years,” March 30, 2015, http://www.eia.gov/todayinenergy/detail.cfm?id=20572.
9. EIA, “What Drives Crude Oil Prices?,” http://www.eia.gov/finance/markets/supply-opec.cfm.
10. Tyler Durden, “The First Shale Casualty: WBH Energy Files for Bankruptcy; Many More Coming,” Zero Hedge, January 8, 2015, http://www.zerohedge.com/news/2015-01-07/first-shale-casualty-wbh-energy-files-bankruptcy-many-more-coming.
11. “Oil Price Fall Forces North Dakota to Consider Austerity,” New York Times.
12. Timiraos, “Oil Price Drop Hurts Spending on Business Investments.”
13. Philips, “The American Oil Boom Won’t Last Long at $65 per Barrel.”
14. Tully, “The Shale Oil Revolution Is in Danger.”
15. Mehreen Khan, “United States Will Not Become the ‘New Saudi Arabia’ of Global Energy,” The Telegraph, February 26, 2015, http://www.telegraph.co.uk/finance/newsbysector/energy/oilandgas/11436337/United-States-will-not-become-the-new-Saudi-Arabia-of-global-energy.html.
16. This analysis focuses on oil primarily because of its dominance in the global energy trade and in geopolitics. Trends covered here also apply to domestic production of natural gas from shale.
17. Michael Fitzsimmons, “Statoil: U.S. Shale Overview and Company Update,” Seeking Alpha, December 22, 2014, http://seekingalpha.com/article/2771615-statoil-u-s-shale-overview-and-company-update.
18. Jennifer Warren, “US Shale Trends Indicated by Production Prowess of Pioneer and RSP Permian,” Concept Elemental, April 2, 2015, http://seekingalpha.com/article/3033816-u-s-shale-trends-indicated-by-production-prowess-of-pioneer-and-rsp-permian?ifp=0.
19. Henry Stokman, “Why EOG Is Primed for High Future Returns,” Seeking Alpha, March 3, 2015, http://seekingalpha.com/article/2970386-why-eog-is-primed-for-high-future-returns.

25. EIA: Yearly production rates in Eagle Ford shale formation showing rapidly increased initial rates of production, 2009–14.
26. "Whiting Petroleum: What the Future Holds," March 9, 2015, http://seekingalpha.com/article/2984106-whiting-petroleum-what-the-future-holds?ifp=0.
27. Sandy Fielden, "When the Sand Goes Down: Prospects for Fracking Proppants After the Price Crash," March 22, 2015, RBN Energy, https://rbnenergy.com/when-the-sand-goes-down-prospects-for-fracking-proppants-after-the-price-crash.
28. Brian Robson, "The Engineering Genius of Fracking: A Study in Mechanical Excellence," March 4, 2015, http://breakingenergy.com/2015/03/04/the-engineering-genius-of-fracking-a-study-in-mechanical-excellence/?utm_source=Breaking+Energy&utm_campaign=b588bb86ac-RSS_EMAIL_CAMPAIGN&utm_medium=email&utm_term=0_f852427a4b-b588bb86ac-407307749.
29. EIA, "U.S. Natural Gas Marketed Production," http://www.eia.gov/dnav/ng/hist/n9050us1m.htm.
30. Some of the continued output is associated with gas produced unintentionally from wells drilling for oil, and from previously drilled wells that, in order to maintain lease requirements, are forced into production.
31. See http://www.eia.gov/todayinenergy/detail.cfm?id=20212.
32. Mark P. Mills, "Prime the Pump: The Case for Repealing America's Oil Export Ban," July 2014, Manhattan Institute for Policy Research.
33. EIA, "2015 Summer Fuels Outlook," April 7, 2015, http://www.eia.gov/forecasts/steo/special/summer/2015_summer_fuels.pdf.
34. Spears & Associates, "Drilling Market Outlook," March 2015, USAEE Houston, http://www.usaee.org/chapters/documents/Houston_USAEE_March%2012%202015.pdf; and http://www.bloomberg.com/news/articles/2015-03-06/introducing-fracklog-the-new-fangled-oil-storage-system-energy.
35. Under some land-lease contracts, however, operators face finite timelines for starting production in order to retain their leasing rights. Such contracts force certain operators to continue production—at a loss or diminished profit—in the expectation of reaping the benefits of higher future oil prices.
36. Nasta, "Every Rig You Take."
37. Spears & Associates, "Drilling Market Outlook," March 2015; and "Lower 48 Oil Economics Still Robust, Wood Mackenzie Says," World Oil, March 25, 2015, http://www.worldoil.com/news/2015/3/25/lower-48-oil-economics-still-robust-wood-mackenzie-says.
38. Foro Energy, http://www.foroenergy.com.
39. Bob Pilko, Blade Energy Partners, private communication.
40. Ball, "Making the Bakken and Niobrara Economic."
41. Keith Holdaway, "Harness Oil and Gas Big Data with Analytics, https://books.google.com/books?id=hwaIAwAAQBAJ&pg=PT23&lpg=PT23&dq=Moray+Laing+oil+data&source=bl&ots=EXGltUji9X&sig=WFBeczx6O7C8UFysvkkTVGfeIU4&hl=en&sa=X&ei=sAgXVa23LMWuggT0uIKYAQ&ved=0CEYQ6AEwBw#v=onepage&q=Moray%20Laing%20oil%20data&f=false.
42. Dallas Salazar, "EOG Resources' 'Trust Me' Story Might Just Be Trustworthy," Seeking Alpha, February 27, 2015, http://seekingalpha.com/article/2958456-eog-resources-trust-me-story-might-just-be-trustworthy.
43. Doug Henschen, "ConocoPhillips Taps Big Data for Gas Well Gains," InformationWeek, September 5, 2013, http://

47. Henschen, "ConocoPhillips Taps Big Data for Gas Well Gains."
48. Karen Boman, "Marriage of Analytics, Engineering First Principles Needed in Oil and Gas," Rigzone, October 31, 2014, http://www.rigzone.com/news/oil_gas/a/135690/Marriage_of_Analytics_Engineering_First_Principles_Needed_in_Oil_and_Gas/?all=HG2.
49. For some operators, a significant share of wells drilled miss the "sweet spots" and are entirely unproductive.
50. Robert Stowe England, "Will Oil Price Collapse Hit Bakken Output?," Institutional Investor, February 9, 2015, http://www.institutionalinvestor.com/article/3425863/asset-management-macro/will-oil-price-collapse-hit-bakken-output-dont-count-on-it.html#.VRgCh0t5DRp; and "Lower 48 Oil Economics Still Robust, Wood Mackenzie Says," World Oil.
51. Spears & Associates, "Drilling Market Outlook," March 2015; pre-2009 data from http://investors.timkensteel.com/files/TimkenSteel%20Investor%20Day%20Presentation_June%2019,%202014_v001_v00gh2.pdf.
52. Jeffrey Yaris, Halliburton, personal communication; 50 to 500 kB/s data rate logging while drilling. Baker Hughes maximum drill rate, 5 ft./min. = 0.1 ft./sec. => ~ 1MB/ft.
53. David Wethe, "Better Fracking Through Sound-Sensing Fiber Optics," Bloomberg, July 11, 2013, http://www.bloomberg.com/bw/articles/2013-07-11/better-fracking-through-sound-sensing-fiber-optics.
54. "Halliburton CEO Sees Recovery in Hydraulic Fracturing Market," World Oil, April 21, 2014, http://www.worldoil.com/news/2014/4/21/halliburton-ceo-sees-recovery-in-hydraulic-fracturing-market.
55. 785 aircraft for Delta, if average 36,000 hp for Boeing 737.
56. See http://www.zdnet.com/article/healthcare-turns-to-big-data-analytics-for-improved-patient-outcomes.
57. a) Assume for 300,000 wells and average of 2 TB/well g 600 PB, http://www.matimop.org.il/uploads/general_files/eldad_weiss_-_og_technology_conference_v1.2_-pdf.pdf; b) Ayata, private communication: 1.5 to 15 TB data per well; c) Wethe, "Better Fracking Through Sound-Sensing Fiber Optics"—fiber sensor well, 15 TB/week. Eldad Weiss, "Collecting and Analyzing Big Data for O&G Exploration and Production Applications," October 15, 2013, Paradigm, G&G Technology Seminar.
58. Perry Rotella, "Is Data the New Oil?," Forbes, April 2, 2012, http://www.forbes.com/sites/perryrotella/2012/04/02/is-data-the-new-oil.
59. See http://www.valuewalk.com/2011/11/bill-gates-energy-innovation.
60. EIA, "Drilling Productivity Report," April 2015, http://www.eia.gov/petroleum/drilling.
61. Christoph Kost et al., "Levelized Cost of Electricity: Renewable Energy Technologies," Fraunhofer Institute, November 2013, http://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/study-levelized-cost-of-electricity-renewable-energies.pdf; http://www.nrel.gov/docs/fy13osti/60207.pdf; "Wind Plant Cost of Energy: Past and Future," NREL, 2013, http://www.nrel.gov/docs/fy13osti/57841.pdf; and Björn Nykvist and Måns Nilsson, "Rapidly Falling Costs of Battery Packs for Electric Vehicles," Nature, March 23, 2015, http://www.nature.com/nclimate/journal/v5/n4/full/nclimate2564.html.
62. David Feldman et al., "Photovoltaic System Pricing Trends," U.S. Department of Energy, September 22, 2014, http://www.nrel.gov/docs/fy14osti/62558.pdf.
63. Louis Columbus, "Where Big Data Jobs Will Be in 2015," Forbes, December 29, 2014, http://www.forbes.com/sites/louiscolumbus/2014/12/29/where-big-data-jobs-will-be-in-2015.
64. Karen Boman, "Data Scientists in Demand in Oil, Gas to Address Big Data Challenge," Rigzone, May 5, 2014, http://www.rigzone.com/news/oil_gas/a/132874/Data_Scientists_in_Demand_in_Oil_Gas_to_Address_Big_Data_

oil-giants-break-their-picks-trying-to-crack-non-u-s-shales-1426735258.

69. "Transport and Its Infrastructure," IPCC, 2014, chap. 5, http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter5.pdf.
70. EIA International Energy Statistics, http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=5&aid=2&cid=ww,&syid=1986&eyid=2013&unit=TBPD.
71. EIA, OPEC marginal supply report.
72. Michelle Ye Hee Lee, "You Can't Trust the Numbers on the New Fracking Regs," Washington Post, March 30, 2015, http://www.washingtonpost.com/blogs/fact-checker/wp/2015/03/30/you-cant-trust-the-numbers-on-the-new-fracking-regs.
73. Edward Dodge, "On Obama's 'Solar Ready Vets' Program," April 11, 2015, Energy Collective, http://theenergycollective.com/ed-dodge/2214946/energy-quote-day-obama-s-solar-ready-vets-program?utm_source=feedburner&utm_medium=email&utm_campaign=The+Energy+Collective+%28all+posts%29.

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