Industrial and Corporate Change, 2024, **33**, 106–125
DOI: https://doi.org/10.1093/icc/dtad021
Advance Access Publication Date: 19 June 2023
Original Article

The organizational and technological origins of the U.S. shale gas revolution, 1947 to 2012

Rahul Kapoor[1,*] **and Johann Peter Murmann**[2]

[1]The Wharton School, University of Pennsylvania, Philadelphia, PA 19104, USA.
e-mail: kapoorr@wharton.upenn.edu and [2]Institute of Management and Strategy, University of St. Gallen, Dufourstrasse 40a, St. Gallen 9000, Switzerland. e-mail: j.peter.murmann@unisg.ch
*Main author for correspondence.

Abstract

We explore the origins and the development of hydraulic fracking technology that made possible United States' unexpected rise as a top producer of oil and gas. As hydraulic fracking was first used extensively to produce shale gas and only later to produce shale oil, we focus on analyzing what is often referred to as the "shale gas revolution." We trace how the shale gas ecosystem evolved, what role different actors played in the unexpected shale gas revolution, and how the strategies and knowledge bases of the different actors differed and evolved over time.

JEL classification: M10, M13, N12, N52, N82, O13, O30

1. Introduction

On November 12, 2012, one of the most stunning headlines appeared seemingly out of nowhere on the front page of the New York Times: "U.S. to Be World's Top Oil Producer in 5 Years, Report Says" (Rosenthal, 2012). How could that be? The first lines of the article provided even more surprising details: "The United States will overtake Saudi Arabia as the world's leading oil producer by about 2017 and will become a net oil exporter by 2030, the International Energy Agency said Monday." Did we not hear for decades that U.S. dependence on foreign oil would last forever? Did we not read in the *Wall Street Journal* that "in the early 1970s, the U.S. sought to use Iran as a stabilizing force in the Persian Gulf to guarantee oil flows without putting U.S. troops in the region" (House, 1997), suggesting that peace in the Middle East was important to U.S. energy security. Why did the attentive reader of leading newspapers never hear that the United States stood a chance to become independent of foreign oil using a novel technology called "hydraulic fracking" that could produce oil and gas from hitherto unrecoverable shale rock formations? Why did the U.S. Energy Information Administration (EIA) not foresee a dramatic increase in U.S. energy production from shale (U.S. Energy Information Administration, 2000; Joskow, 2015)?

Motivated by this surprising development, we set out to investigate this unexpected growth in the U.S. hydrocarbon production. We learned that advances in extracting hydrocarbons from shale using hydraulic fracking technology were first made for the extraction of gas and only later for oil. For this reason, we focus on understanding how the growth in U.S. shale gas production

© The Author(s) 2023. Published by Oxford University Press in association with Oxford University Press and the Industrial and Corporate Change Association.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs licence (https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial reproduction and distribution of the work, in any medium, provided the original work is not altered or transformed in any way, and that the work is properly cited. For commercial re-use, please contact journals.permissions@oup.com

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

came about. It is an industry context that industry evolution and strategy scholars, who have typically focused on the conventional oil industry (Teece, 1980; Helfat, 1997), have not yet studied in any detail. We explored the pattern of technological progress with respect to hydraulic fracking, which is the process through which shale gas is extracted from shale deposits. We also researched the role played by the different actors within the shale gas ecosystem in terms of accumulating technological know-how and commercializing shale gas production. Our aim was to investigate whether hydraulic fracking technology was a radical technology that developed very rapidly and, therefore, caught everyone by surprise as was the case, for example, with synthetic dye technology (Murmann, 2003). Moreover, we sought to understand how the shale gas ecosystem evolved, what role different actors played in the unexpected shale gas revolution, and how the strategies and knowledge bases of the different actors differed and changed over time.

2. Method

We employed a historical method to understand the origins of the U.S. shale gas revolution (Bloch, 1953; Stern, 1973; Gaddis, 2002; Murmann, 2020). We first read the existing accounts in newspapers (e.g., Mouawad, 2009) and the emerging literature (Trembath *et al.*, 2012) on this topic. We were also able to enrich the historical method with interviews of leading witnesses who lived through the decades before and during the shale revolution. In our early readings, we came across Professor Terry Engelder, a leading shale geologist from Penn State University, and we were able to interview him multiple times relatively early in our investigation to find out what experts did and did not know about the possibility of extracting gas from shale. To track as to what extent different actors had anticipated the possibility that shale rock could become a new source of hydrocarbons and invested to take advantage of that opportunity, we chose to examine the nature of research and development (R&D) activities related to hydraulic fracking technology. We drew on the patent data to track the R&D efforts by the different actors well before the growth in shale gas production took place (e.g., Eggers, 2014; Kapoor and Klueter, 2020). We considered that technological progress is shaped by broader innovation ecosystem comprising the focal technology, the upstream components, and the downstream complements (e.g., Adner and Kapoor, 2010). Accordingly, we identified the relevant technological components and complements that encompassed the hydraulic fracking innovation ecosystem, as well as the respective patent classes.

As our research unfolded, other researchers came out with working papers and publications on the shale gas revolution (e.g., Cahoy *et al.*, 2013). Most relevant for investigating the commercialization of shale gas were the publications by Wang and Xue (2014) and Wang and Krupnick (2015). Wang generously shared with us the data on all shale gas wells that were drilled in the six major modern shale gas fields—Barnett, Marcellus, Haynesville, Eagle Ford, Woodford, and Fayetteville—in addition to the Devonian shales in the Appalachian basin. Legal regulations require that every well that is put into production needs to be recorded with the government. This means that data on commercial activities in shale gas are complete and one can determine for any given year how many wells are operated by what firm. To discern how important different commercial actors were in developing the shale gas industry, we coded the well data further by identifying startup and incumbent firms of various types. We did this by researching the history of every firm and determining the founding year and the entry year based on when it first operated a shale well.

To understand better how the major international oil and gas companies (BP, Chevron, ExxonMobil, and Shell) and the upstream service companies (Baker Hughes, Halliburton, and Schlumberger) viewed the prospects of hydraulic fracking, we did a computerized analysis of annual reports of major oil and gas firms and major upstream firms, tracing how often they mentioned fracking (and synonymous terms) in their annual reports. We benchmarked this against the frequency at which fracking was mentioned in a major oil and gas industry publication, "Platts Oilgram News."

At various stages of the research, we interviewed other experts to help us solve apparent puzzles. For example, why did major oil and gas companies patent in hydraulic fracking technology before the shale gas revolution but did not pursue production of shale gas when the technology

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

was ready? We interviewed the former Chief Technology Officer of Shell, van der Eijk (2020), who held that responsibility during the nascent period of emergence of shale gas and clarified for us that the early fracking patents we were identifying for the major oil and gas companies may not be for shale gas fracking *per se* but rather for fracking conventional reservoirs of oil and gas. In Section 3, we provide a historical overview of hydraulic fracking technology. This is followed by an analysis of how the different commercial actors contributed to the rapid growth in the production of shale gas. Finally, we offer a discussion of our findings and point to avenues for future research.

3. Historical overview of hydraulic fracking

The technology that made it possible for the United States to tap its vast resources of gas and oil that were trapped in deep rock formations is sometimes called hydraulic fracking and sometimes hydraulic fracturing. Simply put, through hydraulic fracking, a well is stimulated to produce hydrocarbons by injecting a pressure fluid composed of water, sand, and chemicals that cracks open bedrock low-permeability formations and allows hydrocarbons to collect in the well and be transported to the surface. Hydraulic fracking enabled extraction of gas from shale rock formation that, until the late 1990s, could not be extracted in an economically efficient way. In an interview, Professor Terry Engelder (2014b), the aforementioned leading shale geologist from Penn State University, explained that for decades, geologists knew that vast amounts of gas were trapped in shale rock formations across the continental United States. Figure 1 shows the major U.S. shale gas areas in the lower 48 states. Although the first fracking experiments were done in 1947 (Manfreda, 2019), not until 1998 did a commercially viable shale gas fracking operation take place (Zuckerman, 2014), when George Mitchell's natural gas company—after trying for over two decades—succeeded in TX. Leading up to Mitchell's breakthrough, severe doubt existed whether shale gas could ever be produced at costs so as to be competitive with other sources of energy. This is one of the reasons why energy production forecasts until 2012 did not foresee that the United States would become a net exporter of gas and oil.

Our research revealed that the hydraulic fracking innovation ecosystem is composed of a number of upstream and downstream interdependent technologies that all needed to mature to make shale gas and shale oil drilling economically viable (e.g., Adner and Kapoor, 2010). In this article, we will mainly focus on shale gas fracking because this segment of the energy sector developed

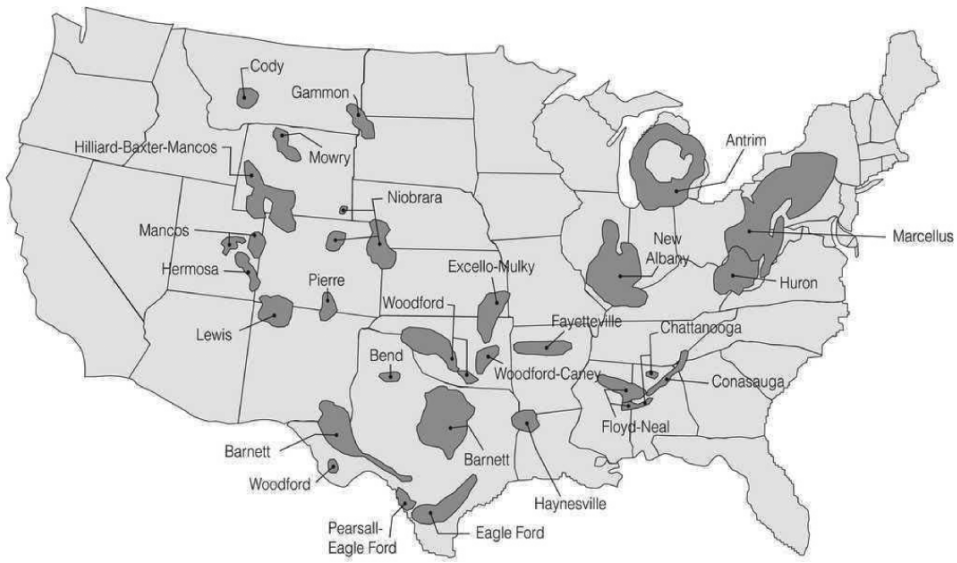


Figure 1. Major U.S. shale gas areas (Source: U.S. Department of Energy, 2009)

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024



Figure 2. First attempt to commercially frack by Halliburton, 1949 (Source: American Oil and Gas Reporter, August 2012) *Note*: Halliburton is still a leading *Oil and Gas Field Service supplier*.

sooner than shale oil fracking. However, in the final Section 5 of the paper, we discuss that during the past decade, hydraulic fracking dramatically increased U.S. domestic oil production, contributing significantly to U.S. energy independence and exports.

Our investigation of the history of fracking technology and associated patents reveals that the first patent filed to detail the idea of stimulating rock formations in wells dates to 1865, when Edward A. L. Roberts (1829–1881), a Civil War veteran, received a patent aptly entitled "Improvement in exploding torpedoes in artesian wells" (Roberts, 1865). A small torpedo with explosives was sent into a well and blown up to make the well produce more oil. However, the idea of stimulating wells with fluids rather than explosives was first conceived by Riley Floyd Farris (1911–2003). He was a petroleum engineer with Stanolind Oil and Gas Co, a division of Standard Oil of Indiana. Starting around 1947, Farris and fellow petroleum engineers at Stanolind conducted many hydraulic fracking oil field experiments, calling their approach "hydrafrac technology." The oil and gas industry learned about this new approach because a detailed description of the novel method was offered by Clark (1949), who formed part of Stanolind engineering staff. Stanolind patented Riley's idea under the title "Fracturing formations in wells" (Floyd, 1949), and the method was exclusively licensed to Halliburton, an important oil and gas field service company that goes on to play a prominent role in the evolution of hydraulic fracking. Halliburton saw a potential for this technology not only in wells that became increasingly depleted but also in drilling of new wells (see comment in Clark, 1949: p. 7). Halliburton was involved in using this new "hydrafrac" technology already in 1949 (see Figure 2) and applied it to oil wells. However, application of the technology to new wells in shale gas formations was not economically viable at this stage. The patent records show that in the ensuing decades, several attempts were made to develop the technology by private companies, inventors, and the U.S. government. However, it took another five decades before the technology and related know-how developed so much that the method became commercially viable for fracking new wells in shale gas formations that could not be tapped with conventional gas drilling methods.

Why did it take so long for shale gas fracking to become economically feasible? Fracturing shale gas required progress in an entire innovation ecosystem (Murmann and Frenken, 2006; Adner and Kapoor, 2010) aside from stimulating wells through the focal hydraulic fracking technology. The idea of horizontal as opposed to vertical drilling of gas wells was a key development that made fracking economically viable. Only after 1990 was the technique used extensively for oil drilling and was later ported to shale gas drilling (King, 1993; Kemp, 2014). To expand the radius of horizontal wells, technologies that could turn on and off stages in these horizontal wells were also very important. To understand shale rock formations and where drilling might yield

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

best results, the development of complementary technology of three dimension (3D) imaging, including microseismic surveys (Trembath, 2015; Ong and Munson, 2018), helped to lower the cost of drilling by reducing the number of failed drills that did not yield any results. A related complementary technology that is used in fracking is called "electric logging." It records rock and fluid properties, making it easier to find areas in subterranean formations containing gas and oil. Specialized chemicals mixed with water and sand are injected into shale bedrocks under high pressure, creating fractures and allowing for hydrocarbons to collect in the well and be transported to the surface. Hence, these chemicals represented a key complement within the hydraulic fracking ecosystem (Adner and Kapoor, 2010). What chemicals to use in fracking and the appropriate balance of sand, water, and chemicals required significant research, often via trial-and-error experimentation and learning. Finally, advances in drill heads and drill rigs also contributed to making shale gas fracking more economical.

Another reason why the arrival of economically viable fracking technology for shale gas took so long is that improvement in technologies such as 3D microseismic surveys was a long-term undertaking (Ong and Munson, 2018). Richard Nelson (1959) pointed out several decades ago that private firms do not have an incentive to engage in basic R&D when it is doubtful that they can appropriate the returns from this R&D. The technology of 3D imaging is a case in point. Had it not been for the various government labs that had long-term programs to develop 3D microseismic surveys of rock formations, the rapid and unexpected growth of shale gas may not have materialized.

Studying the history of shale gas fracking, it is striking how important sustained government efforts were in bringing about the shale gas revolution. Our interviewees (e.g., Engelder, 2014a, 2014b; Fisher, 2022) explicitly acknowledged the important role government played in overcoming the hurdles of developing the unconventional shale gas deposits. Previous students of the shale gas revolution (Trembath *et al.*, 2012; Golden and Wiseman, 2014; Trembath, 2015; Ong and Munson, 2018) have extensively documented the many policies and programs of the U.S. government to tap the vast amounts of shale gas trapped in rocks formation all over the continental United States. Ong and Munson (2018) provide a useful pictorial summary (see Figure 3). The Department of Energy (DOE) carried out a massive hydraulic fracturing demonstration from 1975 to 1977 and for the next 20 years helped commercial companies such as Mitchell Energy and Development with their efforts to improve fracking technology. The DOE and an industry consortium called the Gas Research Institute engaged in a public–private partnership to validate the accuracy of microseismic monitoring between 1992 and 1996, after Sandia National Laboratories had made significant advances in the technology between 1981 and 1986. From 1975 to 1991, the DOE worked on improving directional drilling, and the early patents on the method were issued to DOE scientists. In 1991, the DOE collaborated with Mitchell Energy and the Gas Research Institute to map and drill in the Barnett Shale in TX. Early in the 1970s, the DOE also collaborated with the General Electric Company to develop diamond-studded drill bits. The government also encouraged commercial firms to explore drilling in shale gas formations, offering a

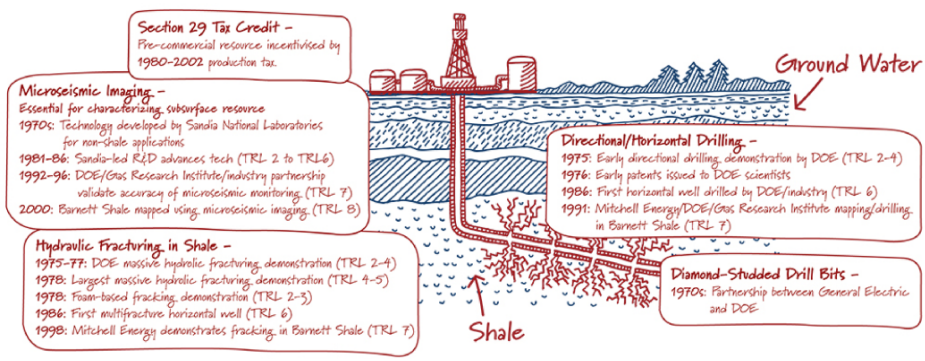


Figure 3. U.S. government role in helping commercialize fracking technology (Source: Ong and Munson (2018))

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

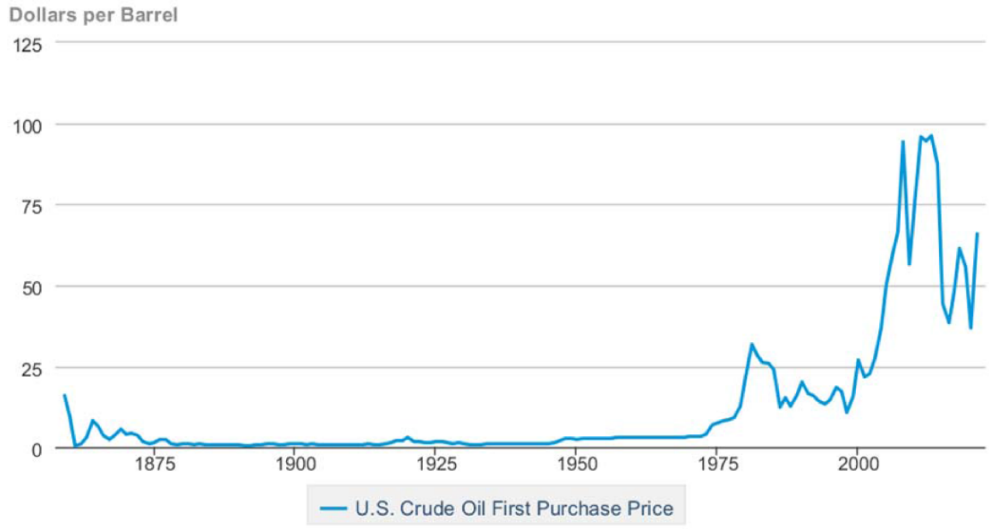


Figure 4. U.S. oil prices (Source: U.S. EIA)

so-called section 27 production tax credit from 1982 to 2002. Ong and Munson (2018) report that over US$10 billion in tax credits were paid out to operators of unconventional wells and the tax credit motivated firms to drill more and collect more data, driving down the costs through learning by doing.

Consistent with earlier work by Helfat (1997), we found a strong correlation: in times of high oil and natural gas prices, U.S. companies invested substantial amounts of resources developing alternative energy technologies (fracking, solar, wind, synthetic fuels, etc.). When energy prices fell, private investments fell. For example, after oil prices rose sharply in the wake of the 1973 oil embargo by Organization of the Petroleum Exporting Countries targeting major Western economies, Western oil firms (and governments) invested heavily into the search for alternative energies. However, between 1980 and 1986, oil prices declined sharply, and oil companies reduced their R&D spending on alternative technologies. A similar decline occurred in the wake of the financial crisis in 2008, which saw more than a 60% reduction in oil price (see Figure 4). U.S. natural gas prices, which were determined largely by U.S. production capacities as opposed to the global supply and demand conditions, did not see these big price swings. Because conventional U.S. gas supplies could not meet demand, natural gas prices rose steadily until 2008, quadrupling since the 1970s (see Figure 5). This provided gas firms ever more incentives to further develop the shale gas fracking technology. High prices also meant that fracking would more readily be able to break even, justifying the capital expenditures (Manfreda, 2019). Once the collection of shale gas technologies had advanced sufficiently and domestic gas prices were high enough to make fracking economically viable, the shale gas revolution took off. It is useful to look at some production figures from 1970 to 2012 to get a sense of the magnitude of the growth in shale gas production. Figure 6 shows that U.S. production volume for natural gas rose dramatically after 2005. Figure 7 supports the idea that shale gas was the source of the dramatic increase, growing from a 2% share to a 40% share of gas production in the United States in 2013. Two years later, the EIA reported the share to reach 50% (U.S. Energy Information Administration, 2016).

The company that first proved the commercial viability of shale gas fracking in 1998 was George Mitchell's Mitchell Energy and Development, which tried for two decades to frack shale gas in TX (Zuckerman, 2014). The company invested significant resources amounting to quarter of a billion dollars drilling in the Barnett Shale between 1981 and 1997 without making a profit (Wang and Krupnick, 2015). As we noted earlier, while Mitchell was aided over the years by government agencies and the Gas Research Institute, its entrepreneurial achievement is widely

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

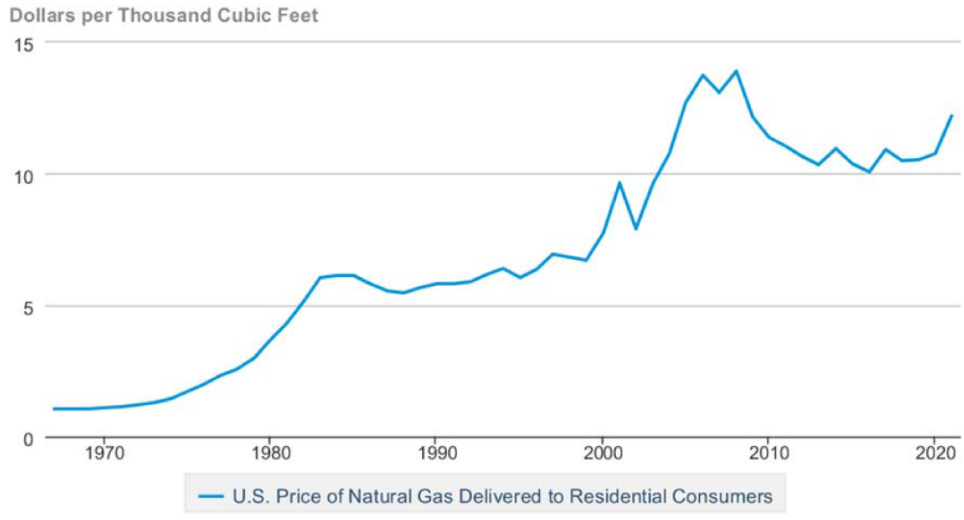


Figure 5. U.S. natural gas prices (Source: U.S. EIA)

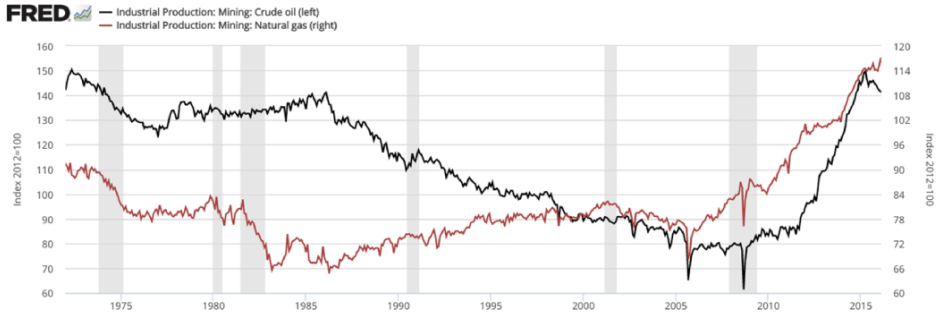


Figure 6. U.S. oil and gas production, 1970–2016 (Source: Federal Reserve Economic Data)

acknowledged. Only in 1998, did Mitchell identify how to use the fracking technologies in the right combination with slick water by using lighter sand (Fisher, 2022). Mitchell's breakthrough became public knowledge in 1999. "Platts Oilgram News" (1999) reported:

> *Mitchell Energy & Development said it has booked 213 Bcf [Billion cubic feet] of new proved natural gas reserves in the Barnett Shale play in North Texas, an increase of 25% in the company's gas reserves at Jan 31, 1999. Mitchell said the increase in reserves is related to a plan to step up development activity at the play, which in turn is driven by the successful application of lower-cost "light sand" fracture stimulation technology. This technology has cut unit drilling and completion costs from $0.64/thousand cubic feet (Mcf) to $0.47. Mitchell said two additional rigs have been contracted to drill a 25-well program in the area in the second half of this year. With the increased drilling and recompletion work, the company expects to double or possibly triple current net output of 74,000 Mcf/d from the Barnett Shale over the next four to five years (Vol 77, No. 177).*

Mitchell had reduced unit drilling and completion costs by 30% and proved that shale gas could be extracted in an economically viable way. This allowed the company to leverage natural gas reserves that previously were not accessible. Mitchell first drilled mainly vertical wells but in 2000 and 2001 drilled more and more horizontal wells with much better results (Fisher, 2022). In 2000, the U.S. government helped to seismically map the Barnett Shale, where Mitchell was drilling, to give a more accurate estimation of how much gas was trapped in the area (Ong and

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

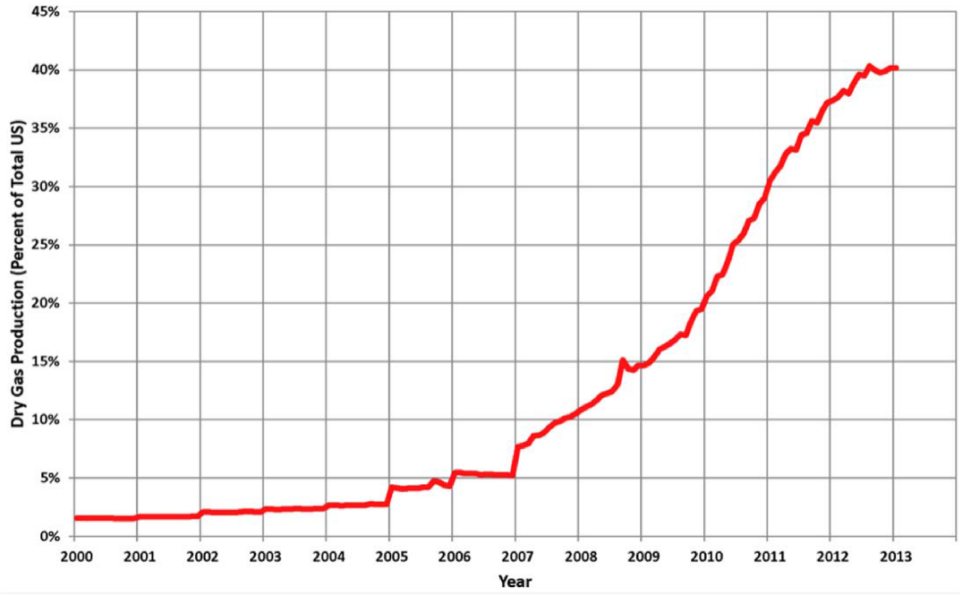


Figure 7. Percent of U.S. natural gas production from shale, 2000–2013 (Source: EIA)

Munson, 2018). In 2001, the 82-year-old George Mitchell sold his company to Devon Energy, making Devon the second-largest independent producer of natural gas in the United States, after previously occupying the fourth position (Sidel and Cummins, 2001). Devon Energy subsequently dramatically expanded the use of horizontal drilling techniques in conjunction with multi-stage fracking and combined Mitchell's techniques with other new technologies, allowing fracking to become much more profitable (Wang and Xue, 2016). Natural gas spot prices rose from around US$1.72 in December to 1998 to US$13.05 in December 2005 (Figure 5), attracting many commercial actors to pursue opportunities in shale gas. In parallel, substantial technological progress took place within the fracking innovation ecosystem after 2000, leading to a large expansion of gas and oil production from shale rock layers, which was fueled by enthusiasm from Wall Street to fund the companies exploiting progress in fracking (Wang and Krupnick, 2015). The pre-existing large network of gas pipelines built from the 1950s to distribute natural gas throughout the United States (see map https://bit.ly/3FvV4hF) facilitated the commercial take-off of shale gas production (Golden and Wiseman, 2014), with a rapid take-off that even surprised the energy experts at the EIA (U.S. Energy Information Administration, 2000: 44).

4. What types of commercial actors brought about the shale gas revolution?

To identify the various commercial actors in the shale gas ecosystem and how they contributed to the unexpected growth of shale gas through hydraulic fracking, we sought to understand the historical background of the different types of actors (Trembath *et al.*, 2012; Golden and Wiseman, 2014; Ong and Munson, 2018), tracked patent trends in relevant technological domains that underlie the fracking technology, and reviewed commercialization trends in terms of the operation of shale wells. The key actors in the shale gas ecosystem are located upstream where exploration and production take place. Midstream are the companies that are responsible for the transportation and storage of gas, and downstream are the companies that market gas to consumer, which vary in terms of their scale and scope. To bring about the shale gas revolution,

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

relatively little changes were required in the midstream[1] and downstream segments of the gas industry. Therefore, one can focus on the upstream players.

It is useful to distinguish between four types of commercial actors: (1) the so-called major integrated oil and gas companies, (2) the service suppliers who provide equipment, materials, and services to the oil and gas companies, (3) the independent oil and gas companies, and (4) the new shale gas startups. We will now describe the main characteristics of these different types of actors in the shale gas ecosystem and how their knowledge bases at time of entry differed from each other. We treat the shale gas ecosystem as a new innovation ecosystem around the hydraulic fracking technology in which multiple actors contributed to the extraction of natural gas from shale deposits that were previously not amenable to extraction.

Traditional oil and gas exploration is a very complex undertaking. Acha (2002) reports that "the most recent PennWell Directory of the offshore oil & gas industry alone listed over 5800 companies categorized by construction contractors, diving contractors, drilling contractors & rig owners, exploration & production companies, geophysical contractors, service companies, suppliers & manufacturers, transportation and workover & well servicing companies (p. 67)." The hallmark of traditional oil and gas exploration projects is the long-term horizon of these investments (Shuen *et al.*, 2014). Before any oil and gas would flow from entirely new locations, about 20 years of exploration and development would be necessary. Oil would then flow for up to 30 years, and it would take between 2 and 10 years to close a well. The life cycle of a project, therefore, ranges between 32 and 60 years. Another characteristic of traditional oil and gas exploration is that at least 30% of drilled wells never produce oil or gas,[2] making it a risky business. Shuen et al. (2014) note that "[u]nconventional [shale] wells are depleted more rapidly than conventional wells, challenging traditional calculations related to the long-term return on investement of leases, transportation and logistical support (p. 9)."

Consistent with the literature, we distinguish between incumbent firms and entrants (Audretsch *et al.*, 2004; Agarwal and Moeen, 2015), and we also broadened the analysis to consider the important role of upstream service suppliers. The largest oil and gas companies, often referred to as supermajor integrated oil and gas companies, are established incumbents, involved in activities that include exploration, production, transportation, storage, refining, and marketing of oil and gas to final users. They tend to be international in scope and typically have market capitalization of US$100 billion or more. BP, Chevron, ExxonMobil, and Shell Global are prominent examples of supermajors. Following the scale and scope of supermajors are major integrated companies that are defined based on the market capitalization of US$10 to $100B, and these may also include national oil companies (NOCs) that leverage the oil and gas reserves of their respective countries, such as Saudi Aramco and China National Petroleum Corporation.[3] These major integrated oil and gas incumbents controlled about 85% of global reserves during the 1950s, and in 2013, 90% of global reserves were under the control of NOCs (Economist, 2013). For the purpose of our analysis, we focus on the major integrated oil companies that are active in the United States.

As indicated by their title, the major integrated oil and gas companies are active in all stages of the value chain from exploration to marketing to final consumption. Since the rise of the automobile in the early 20th century and the ever increasing demand for fuel, the supermajors have been at the top of the list of the industrial enterprises in the economy. In 1929, Exxon predecessor, Standard Oil of New Jersey, topped the Forbes U.S. list, and in 2022, Exxon was sixth on the Fortune list of the largest U.S. companies. Historically, the strength of the supermajors comes from their ability to raise large sums of monies for oil and gas exploration, their technological

[1] Some of the new shale plays were not previously connected to gas pipelines. Shale operators (for example, Antero Resources) in these cases needed to make investments in midstream facilities. However, for the most part, they relied for third party firms to deliver their gas to end markets (See Antero Resources IPO filing https://tinyurl.com/4wchksev).

[2] Here are data on Total's dry well going back to 1949. https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0405. In recent years, the rate of dry wells has gone up to above 75%, 90% onshore and 75% offshore https://tinyurl.com/4twfbsn5.

[3] As governments in recent decades have taken oil concessions out of the hands of the supermajors and given them increasingly to their national oil companies, the market value of some of these NOCs, for example, ARAMCO, has clearly risen above 100 billion. In the case of ARAMCO, it's market value in 2022 stood at 2.2 trillion US$ and Petro China at 142 billion US$ according to the Forbes Global 2000 list (https://tinyurl.com/2cpt4tfa).

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

and project management skills, as well as their global reach. Since the early 20th century, the majors engaged in R&D. For example, Shell opened its R&D center in Amsterdam in 1912 and Shell's American branch, which was separately listed on the New York Stock Exchange, started an R&D lab in Emeryville, CA, in 1928.[4] Standard Oil of New Jersey bought access to a large stock of intellectual capital by acquiring for US$330m (in 2005 dollar), the entire non-German patent portfolio of the German chemical giant IG Farben in 1929 (Bakker, 2013).

In recent decades, the supermajors have also made investments to improve exploration and production technologies. Economist (2013) reports that the supermajors invested $4.4 billion in R&D in 2011 while the oil and gas service companies invested $2.3 billion, and the biggest NOCs invested $5.3 billion. It is important to point out that these figures do not entail expenditures for oil exploration and drilling that are accounted for separately. In 2010, Exxon spent about US$1 billion in R&D (amounting to 0.2% of sales) and US$2.1 billion in exploration expenses (amounting to 0.4% of sales). The R&D intensity of Exxon in 1982 was not much different with 0.15% of sales (US$161 million in R&D and US$102 billion revenue). Other major integrated oil companies have similar R&D intensities except for Total of France, which spent 0.6% of sales (Crooks, 2014). Over the past decades, the major integrated oil and gas companies and the NOCs have increasingly relied on specialized exploration and drilling service suppliers to invest in new drilling and well completion technologies. Where the majors continued to invest heavily was in their geological and seismic abilities to find new sources of oil and gas, using the most advanced supercomputers available in the world (Crooks, 2014). The major integrated companies did not have any experience in drilling shale formations. Given their prevailing business model that entailed long cycles of investment in traditional oil and gas, they lacked both incentives and capabilities to pursue shale plays, opening up the opportunities for other specialized actors. Feiler and Teece (2014) conducted a case study of one of the supermajors, focusing on the different types of dynamic capabilities (p. 16) that were identified and developed by its managers in order to maintain its competitive advantage. Many of these capabilities were organizational in nature, highlighting the need for greater speed and agility, in the evolving industry landscape. Given that the case evidence is from a period after the sales take-off in shale gas, it is suggestive of the organizational challenges that large integrated majors may have confronted in taking advantage of opportunities in shale gas.

In addition to the major integrated oil and gas incumbents, there are a large number of independent oil and gas incumbents (e.g., Devon Energy, Chesapeake Energy, and EOG Resources) that focus on the upstream exploration and production of oil and gas in specific geographical regions in the United States. Unlike the so-called "majors," independent oil and gas incumbents like Devon Energy and Chesapeake did not invest in developing new technologies, as is clear in their annual reports that do not even list R&D expenditures. Instead, they fully rely on the service providers like Schlumberger and Baker Hughes to improve fracking technologies. They are in competition with each other and the major oil companies for securing leases on land where they drill for gas. The big advantage of the independent oil and gas company such as Mitchell Energy, Devon, and Chesapeake is that they make investments decision much more quickly than the major oil companies. A key capability of these firms was to secure drilling leases on the new shale gas plays that emerged in different parts of the United States (see Figure 1). A quote from Zuckerman's (2014) colorful descriptions of the key business people behind the shale revolution highlights how important this capability was for obtaining market share in shale production. "Larry Coshow, a veteran Chesapeake landman, was eager to help McClendon and Ward make up lost ground in the Barnett Shale [in 2005-6]. Coshow knew he had his work cut out for him, so he went on a hiring spree. Soon he was directing over seven hundred brokers to blanket six counties in East Texas, checking records and buying leases, directing twice as many men in local courthouses as any other company. […] Within a year, Chesapeake had overtaken its competitors in the Barnett. The company had purchased over a million acres of land around the country, thanks to the work of over a thousand landmen crisscrossing the nation's fields" (p.198–9).

[4] https://www.informs.org/Explore/History-of-O.R.-Excellence/Non-Academic-Institutions/Shell-Oil-Co.

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

Besides independent incumbents, a number of independent startups were founded to explore opportunities presented by shale gas and oil. These included Antero Resources, Braden Exploration, and Frost Brother Resources, among others. Frequently, these startups were led by people who had previously worked in the oil and gas industry and who could move quickly to secure land where they could drill. Antero resources, for example, was co-founded in 2002 in Denver by Pauly Rady (who has worked as a geologist at Aramco before becoming an entrepreneur) and by Glen Warren (UCLA MBA graduate) after they had sold their previous venture Pennaco Energy to Marathon Oil in 2001. Braden exploration was founded by Bruce Braden (Stanford BA, Golden Gate University MBA) in 2007. He had been the founder of other oil and gas companies focused on exploration of oil and gas such as Stroud Energy formed in Dallas/Fort Worth where he achieved a 50-fold return.[5] In 2012, he also founded the F2 Oilfield Services Company providing well services to large companies like Devon.[6]

Service suppliers are key upstream actors who provide equipment and services for exploration and production of oil and gas. Like oil and gas firms, the service suppliers vary significantly in their scale and scope as it relates to supply of equipment, materials, software, and technologies for exploration and production. The largest service suppliers, Schlumberger, Halliburton, and Baker Hughes, offer a broad spectrum of services around exploration and production, including turnkey operations of drilling sites. As indicated in its annual reports, the R&D intensity of Schlumberger in 1982 was 5.4% (US$326 million at sales of US$6026 million) and 3.3% (US$919 million out of sales of US$2744 million) in 2010 and 2.6% in 2013 (Crooks, 2014). Halliburton, in turn, spent 2.0% on R&D in 2013 (Crooks, 2014). Integrated oil and gas companies did not want to rely on proprietary technology for all their activities, and hence, they have come to rely on the specialized service firms for advances in drill and well completion technologies (Crooks, 2014). The fact that the large service providers had R&D intensity that was 10 times higher than the major integrated oil companies is testimony of this trend. A study of the Norwegian oil sector between 2001 and 2008 confirms that across the entire diverse range of service players, R&D expenditures are higher than for operating companies, with the most intense R&D investments ranging from 10% to 20% of sales in the case of companies providing geological and seismic services (Sasson and Blomgren, 2011).

We performed two types of analysis to understand how the different actors pursued opportunities associated with shale gas. First, we undertook a detailed analysis of patent applications within the PATSTAT global database maintained by the European Patent Office as a proxy for technological investments related to the hydraulic fracking process that enables the extraction of gas from shale deposits. To determine the nature and scope of technologies that make up the hydraulic fracking process, we used a combination of approaches. We read technological histories of hydraulic fracking to understand the different process steps and materials that constitute the overall process. As mentioned earlier, these include 3D imaging and electric logging, well stimulation, horizontal drilling, specialized fracking chemicals, and drill bits. We then used a combination of keyword-based approach and consultations with experts, including several U.S. Patent and Trademark Office patent examiners (David Bagnell, Doug Hutton, and Sue Chung) and a geoscience expert on hydraulic fracking, Terry Engelder (2014a) to identify a number of different Cooperative Patent Classes (CPCs) that correspond to the hydraulic fracking process (see Figure 8). Second, we used data on the number of shale wells drilled in the United States, courtesy of Wang and Xue (2014). The data include the yearly count of shale wells drilled by each firm. We built on these data to identify the different types of actors that operated the shale wells in terms of whether they were integrated oil and gas firms, independent oil and gas incumbent firms, or independent oil and gas startups that were founded to take advantage of opportunities presented by the shale boom.

Figure 9 shows the total number of patent applications related to hydraulic fracking and the total number of shale wells drilled during 1982 to 2012. We note that many of the patent applications during the 1980s and early 1990s may not be directly applicable to shale gas extraction via hydraulic fracking. Rather, our discussions with industry experts

[5] https://www.ggu.edu/press-room/profiles/alumni/bruce-braden.
[6] https://opencorporates.com/companies/us_de/5250767.

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

(van der Eijk, 2020; Fisher, 2022) suggested that those patents might be applicable to somewhat related processes but with respect to conventional oil and gas. Hence, the patent applications data during those years need to be interpreted more cautiously as related to shale gas exploration and production. Setting aside these limitations of the patent data, the general patterns of patenting and shale wells drilled suggest a cumulative process of knowledge accumulation and technological progress and lagged process of industry growth in terms of number of shale wells being drilled.

Interestingly, patent applications surged after 1994, 4 years before the commercial breakthrough in 1998. While we are unable to identify the specific reason for this surge, this period corresponds to efforts by U.S. DOE to develop and commercialize hydraulic fracking. From 1994 to 1998, patent applications rose from 4161 to 7128. They continued to rise but at a slower rate, peaking at 11 305 in 2011. Evidently, the promise of fracking technology became clearer to insiders a few years before the commercial breakthrough in 1998. The take-off in the number of wells drilled took place after 2000, with rapid growth during 2005 to 2008.

We next explore how the different actors in the shale gas ecosystem contributed to the evolution and growth in shale gas. Figures 10 and 11 plot the patent count for firms with the largest number of patent applications within hydraulic fracking processes (CPC E21B codes) and specialized chemicals (CPC C09K codes) that need to be used for the process. Figure 12 plots the number of entrants in the shale gas industry by year based on when they operated the first shale well. Figure 13 plots the count of wells drilled by different types of firms in a given year.

The large integrated oil and gas firms, majors and supermajors, seems to have played a very limited to no role in the growth of shale gas, as evident through their patent applications and operation of shale wells. Prior work has shed some light on how the locus of technological innovation in the oil and gas industry has gradually shifted upstream from oil and gas producers to service suppliers. For example, Acha (2002) documented that the R&D intensities of integrated majors such as Shell, ExxonMobil, and BP were significantly lower than the R&D intensities of

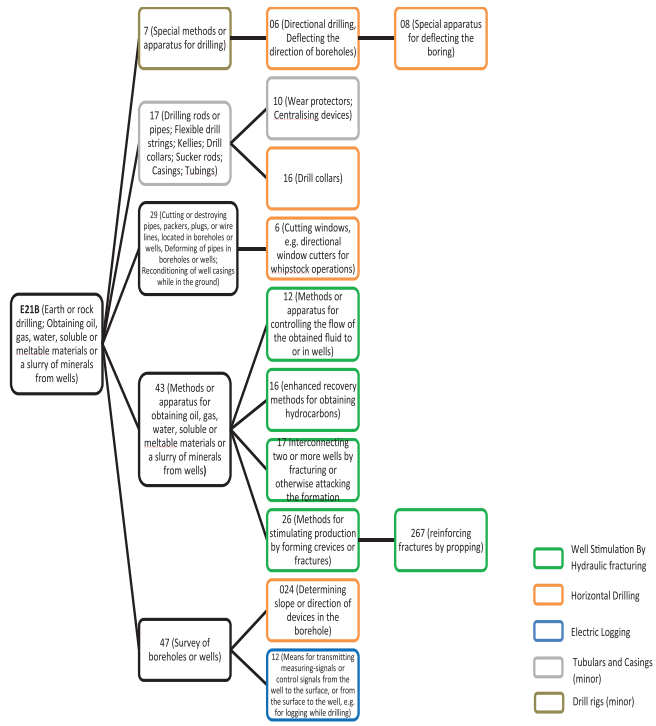


Figure 8. Categories schema illustration of hydraulic fracking–related Cooperative Patent Classification (CPCs)

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

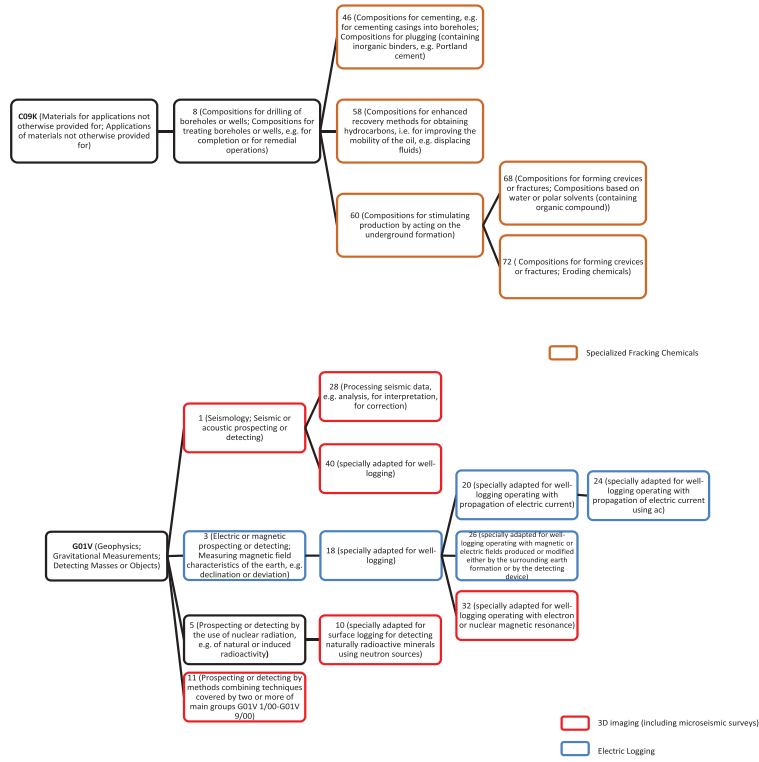


Figure 8. (Continued)

large service suppliers such as Halliburton, Schlumberger, and Baker Hughes. Moreover, there was a gradual preponderance of patenting by these suppliers as compared to oil and gas majors from 1984 to 1997. Similarly, Perrons (2014) found in a survey that service suppliers generated significantly more patents and deployed more new technologies than oil and gas firms. Furthermore, the survey evidence suggested that oil and gas firms relied heavily on the knowledge of service suppliers. We observed a consistent pattern in the case of patenting in hydraulic fracking. Among the firms that were the most active in patenting technologies related to hydraulic fracking, the large service suppliers, Halliburton, Schlumberger, and Baker Hughes, dominated patenting, with integrated oil and gas firms such as Shell and ExxonMobil playing a fairly limited role in developing technological know-how. Hence, the locus of technological innovation and knowledge accumulation with respect to hydraulic fracking resided squarely within the large upstream service suppliers, who saw hydraulic fracking as a significant opportunity to grow their businesses. While large integrated oil and gas majors such as Shell and ExxonMobil engaged in possible exploratory technological investments in hydraulic fracking during the 1980s and 1990s, perhaps as response to rising gas prices, they did not persevere with those explorations. Moreover, the large service suppliers innovated not only in the focal fracking technology but also in the key complement of specialized chemicals as captured in the patenting trend reported in Figure 11.

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

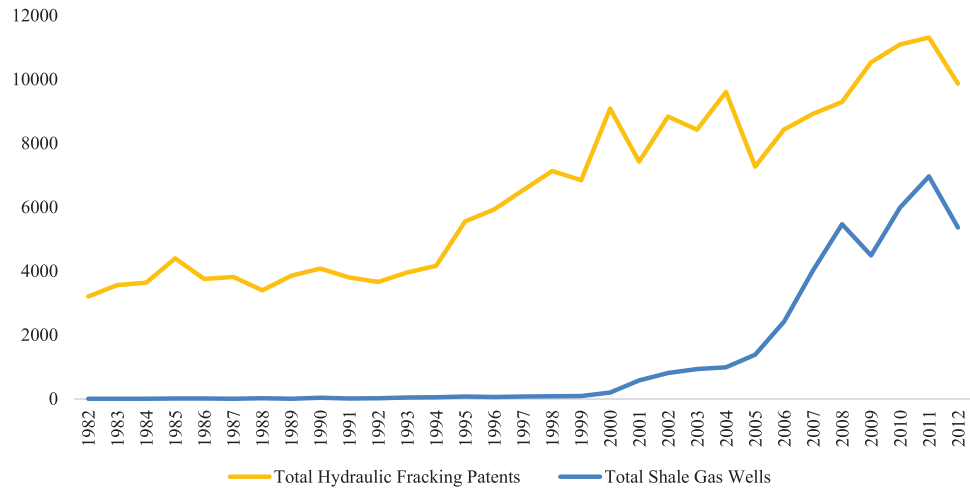


Figure 9. Total hydraulic fracking patent applications and shale gas wells

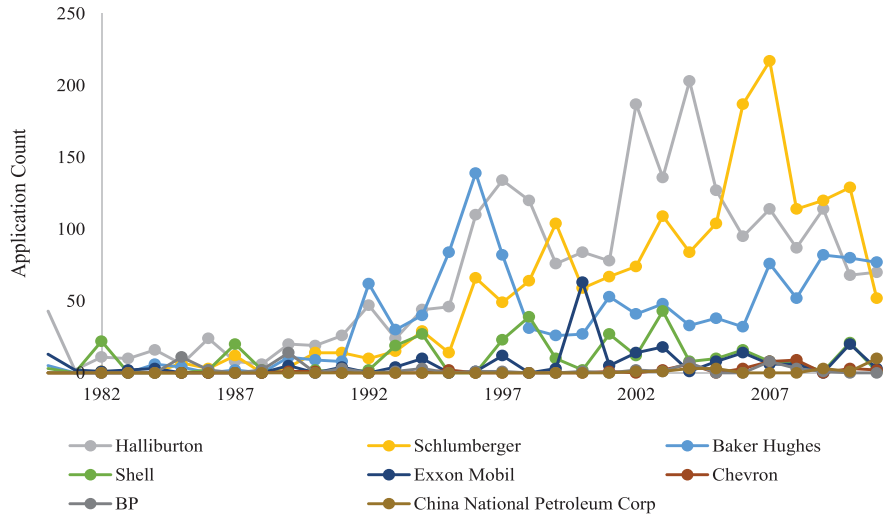


Figure 10. Fracking (CPC E21B Codes) patent applications by oil and gas field service companies and major oil companies

This helped to ensure that progress in fracking technology is not held back by bottlenecks in chemicals in terms of their effectiveness and safety.

The pattern of entry by firms through operating shale wells and the overall well count for the different types of firms show several interesting patterns (Figures 12 and 13). A flurry of entrants emerged after the public knowledge of Mitchell's breakthrough in 1999 with low-cost extraction of shale gas using hydraulic fracking, supported by attractiveness of the industry through rising gas prices. The number of entrants peaked in 2007, with the majority of entrants being incumbent independent oil and gas companies who rushed to take advantage of the new opportunities presented by shale gas. Several startups were also founded during this period and entered the shale gas industry, albeit with a lower rate of entry. At no point did the number of startups outpace the number of incumbent independent oil and gas firms that diversified from conventional gas exploration to fracking of shale gas. Moreover, from 1999 to 2012, the independent oil and gas firms

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

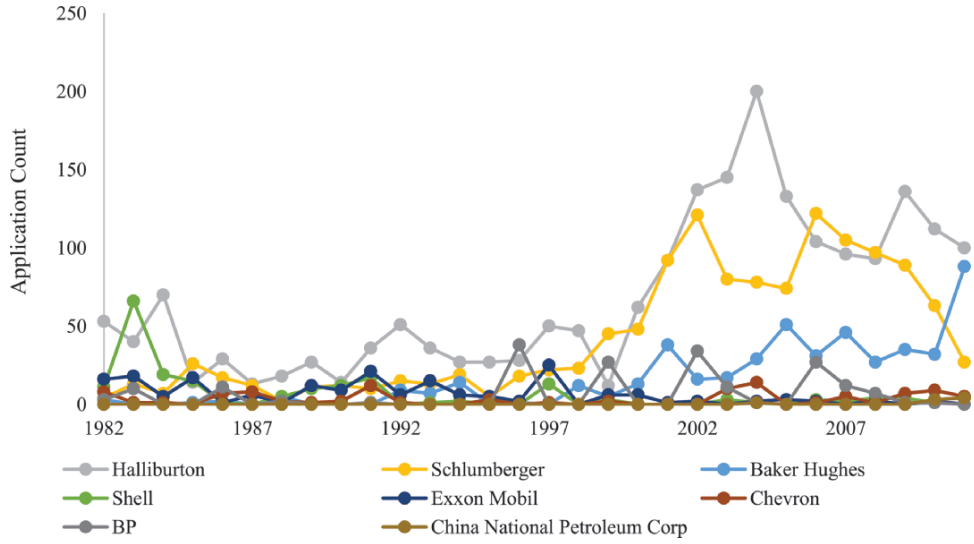


Figure 11. Fracking chemicals (CPC C09K Codes) patent applications by oil and gas field service companies and major oil companies

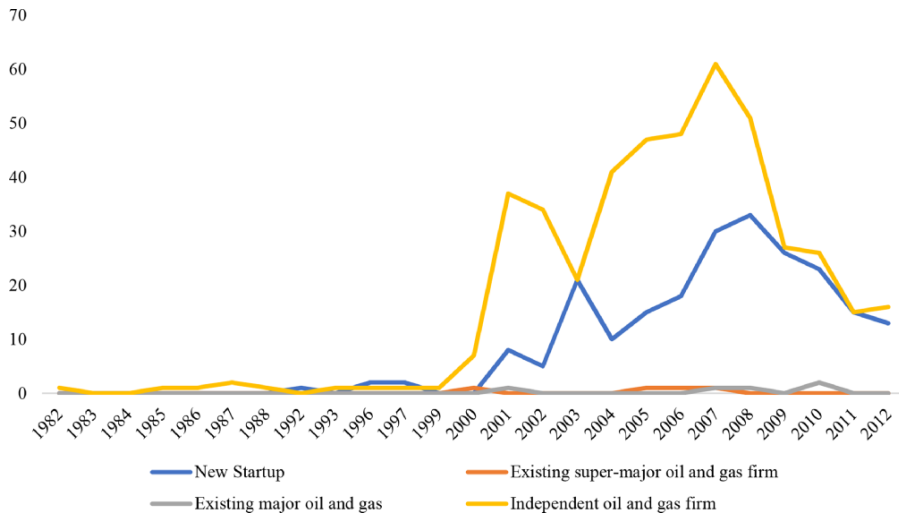


Figure 12. Number of entrants into shale gas industry by type of firm

also drilled the majority of shale wells, followed by startups (Figure 13). The integrated majors played almost no role during this era of shale gas boom. While ExxonMobil made some initial foray in 2000 and several others including BP, Chevron, and Burlington Resources followed later, these firms operated few wells and contributed little to the growth trajectory of shale gas.

Another noticeable feature that emerged from the patent analysis was that the top 30 operators of shale wells collectively had a handful of patent applications in hydraulic fracking. A case in point is Mitchell Energy Corp., the industry pioneer, with only a single patent application filed in 1985. Chesapeake Energy Corp., the largest operator of shale wells, also had a single patent application during 1982 to 2012, which was filed in 1997. Hence, these firms focused on production but did not have the scale or scope to develop technological know-how related to hydraulic fracking. Instead, they were able to leverage the markets to deploy the technological know-how of large service suppliers that facilitated extraction of shale at low cost and allowed

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

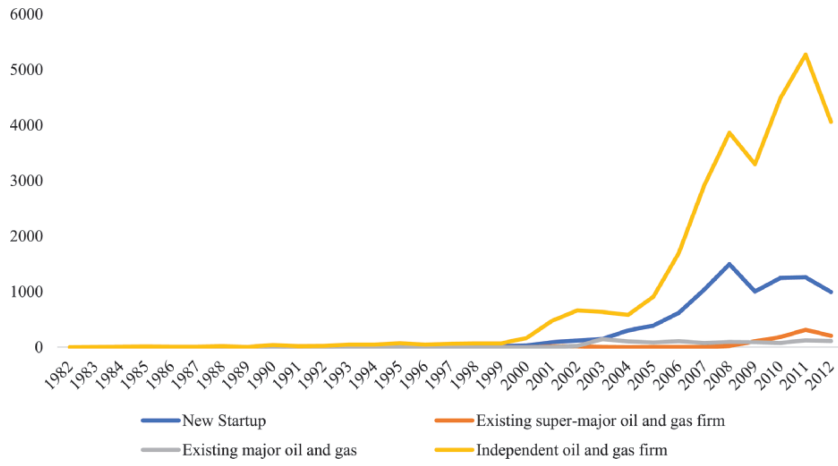


Figure 13. Yearly number of shale wells drilled by type of firm

them to focus on commercialization in terms of identification and acquisition of shale wells, operating the wells, and coordinating downstream activities related to storage, transportation, and sales.

These patterns illustrate that the growth in shale gas did not stem from a sudden technological discontinuity that was triggered by either entrants or established incumbents, as is typically viewed in the industry evolution literature (Anderson and Tushman, 1990; Christensen, 1997). Rather, it was shaped by gradual and cumulative efforts by upstream service suppliers who contributed significantly to the development of know-how and the downstream incumbent specialized oil and gas firms who contributed significantly to commercialization. The incumbent supermajor oil firms played virtually no role in bringing about the shale gas revolution. Only when fracking of shale gas had become the dominant source of natural gas, did they enter the industry at scale, mainly by acquiring existing independent oil and gas companies, such as the case of Chevron acquiring the third-largest shale gas driller, XTO, in 2010.[7]

5. Discussion and conclusion

The objective of this study is to explain the rapid growth of shale gas production in the United States at the dawn of the 21st century leading to the unexpected dominance of the United States as a major global producer of oil and gas. The growth was sculpted through major advances in hydraulic fracking technology that provided an economically viable way to extract shale gas. We go beyond existing patent studies of fracking (Cahoy *et al.*, 2013) by tracking the entire collection of technologies required for fracking gas and connecting the technological evolution to the commercial development of the shale gas industry. As our analyses revealed, the advances in hydraulic fracking technology were not characterized by a major technological discontinuity. Nor were they shaped by new entrants or large established incumbents, as is often viewed within the industry evolution literature. Rather, what seemed like a radical change at the industry level

[7] In order to explore whether our inferences from the patenting trend may mask the possibility that integrated oil and gas firms may be patenting less but developing more valuable patents, we collected additional fracking patent data from Derwent Innovation Index that we were able to access recently. Derwent Innovation Index is a proprietary patent database that includes patents granted worldwide and has a dedicated technology classification for fracking or fracturing (H01-C03). A single patent record in the database is referred to as a patent family which can include multiple patent applications or grants in different patent jurisdictions related to the same invention. We looked through the top 100 patent families with the highest forward patent citation as a proxy for patent's value. Of this sample, 62 patent families belonged to service suppliers, followed by several specialty chemical manufacturers such as Dow Chemical and Hexion. Noticeably, of all the integrated oil and gas firms, there were only two patent families that were assigned to Mobil Oil Corp and only one to Shell.

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

took place through a gradual cumulative evolutionary process at the ecosystem level where different actors played distinct roles in terms of development of technological know-how and actual commercialization.

Our patent-based analysis revealed that the locus of technological innovation and the accumulation of technological know-how related to hydraulic fracking resided in large upstream suppliers such as Halliburton, Schlumberger, and Baker Hughes. These actors operated in an incentive regime in which their ability to create value over time was based on growth in exploration and production of oil and gas, and shale gas presented an important opportunity for them to tap into vast amounts of unconventional oil and gas reserves in the United States. Moreover, their large scale and scope allowed them to sustain their level of exploratory investments even if the market for shale gas had not yet taken off.

The important role of the U.S. government in providing financial and technological support through investing in R&D of core technologies, carrying out drilling experiments, providing tax credits, and entering public–private partnerships during the nascent period of this industry's evolution cannot be neglected. We are certainly not the first ones to remark on the importance of government involvement in helping to bring about technologies where private parties cannot appropriate returns from their R&D (Nelson, 1959; Mazzucato, 2015). Consistent with Nelson's (1995) suggestion that firms should partner through industry consortia to solve technological problems that hold back the entire industry, gas firms through its Gas Research Institute partnered with each other and the government to solve the bottlenecks in the fracking innovation ecosystem.

The locus of commercialization took place within specialized incumbents (independent oil and gas firms) and to a lesser extent, independent oil and gas startups, and not within integrated majors. Hence, the commercialization of shale gas during the early phase of emergence and growth did not conform to the Stiglerian perspective (Stigler, 1951), according to which integrated firms populate the emergence stage of an industry and only when the demand for the focal good increases, does it become viable for specialized firms to enter and carry out operations that exhibit increasing returns to scale. The growth in the shale gas industry exhibited an opposing trend in which growth was spurred by specialized firms, and integrated firms entered the industry at a much later stage.

We also did not observe a major role of markets for technology as has been observed in the emergence and growth of biopharmaceutical and several chemical industries (Arora *et al.*, 2001). Instead, the emergence and growth of shale gas industry were enabled by pre-existing markets for services between large upstream service suppliers and downstream specialized incumbents. While the specialized incumbents did not have the scale to develop their own technological knowledge base for hydraulic fracking, the market mechanism allowed for a clear division of labor. Upstream suppliers developed the core technological know-how and appropriated value through the provision of services, and downstream independent oil and gas firms owned shale wells and appropriated value through their shale asset base, operational efficiencies, experimentation, and even secrecy with respect to chemical combinations used for hydraulic fracking (Fetter *et al.*, 2020).

In summary, the case study of unexpected growth in U.S. shale gas not only sheds light on an important episode of industry evolution that dramatically shifted the global landscape for oil and gas but also explicates a novel theoretical account of an industry's evolution. This account suggests that sometimes sudden industry growth may not be the result of a radical technological discontinuity shaped by large established incumbents or new entrants but rather by a gradual cumulative process encompassing multiple actors in the ecosystem who perform distinct roles in terms of development of technological know-how and downstream commercialization.

We focused in this article on shale gas and not the subsequent take-off of shale oil. In recent years, as the number of conventional oil reservoirs in the United States has decreased, hydraulic fracking technology has been extensively used in U.S. oil production as well. The Congressinoal Research Service (2015) estimates that 90% of new U.S. oil and gas wells by 2015 employed hydraulic fracking technology. The dramatic rise of U.S. domestic oil production after 2010, as shown in Figure 6, is not conceivable without the development of the fracking technology. There are strong links between the development of the gas and oil industries that future research could investigate in more detail. As we noted in our historical overview (Section 3), fracking

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

and horizontal drilling were first experimented with in the conventional oil industry. Then, the technology was adapted over decades to unconventional shale gas deposits. After the technology became commercially viable in natural gas, it appears that technological improvement has been reimported in the oil industry, reminiscent of technological dynamics articulated by Levinthal (1998). A clear link between gas and oil industries is upstream service suppliers such as Halliburton, Schlumberger, and Baker Hughes that support both industries. However, at first glance, the dynamics of the two industries are not identical. While the major oil and gas companies did not play a significant role in shale gas, they seem to have played a more prominent role in the later development of the shale oil industry. In 2020, Chevron had become the largest shale oil producer in the United States and ExxonMobil came in as the fifth-largest producer (Statista, 2020). How did such integrated majors achieve a high market share in the case of shale oil, in contrast to their limited role in shale gas, is another important question to explore.

The emergence of shale oil and gas presents an important opportunity for industry evolution scholars to unpack the roles and the importance of heterogeneous actors in shaping technological progress and economic growth. We hope that our article is an important first step in that direction.

Acknowledgements

We would like to thank Professor Terry Engelder at Pennsylvania State University for invaluable help with understanding the history of the shale gas revolution and providing us with an overview of all the technologies required for extracting shale gas. We are also grateful to David Bagnell, Sue Chung, and Doug Hutton at U.S. Patent and Trademark Office for their help with identifying the relevant patent classes for our analyses. Zhongmin Wang generously shared with us data on all U.S. shale gas wells. Kevin Fisher (fracking expert) and Jan van der Eijk (former CTO of Shell) also helped us understand the history of hydraulc fracking and the relevant technological context. Yejia Li, Stuart Sun, and Daniel Wilde provided excellent research assistance.

References

Acha, V. L. (2002), 'Framing the past and future: the development and deployment of technological capabilities by the oil majors in the upstream petroleum industry,' Doctoral Dissertation. Univeristy of Sussex, Available at SSRN 1357624.

Adner, R. and R. Kapoor (2010), 'Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations,' *Strategic Management Journal*, **31**(3), 306–333.

Agarwal, R. and M. Moeen (2015), 'Entrepreneurial startups (*de novo*), diversifying entrants (*de alio*) and incumbent firms,' in M. Augier and D. J. Teece (eds), *The Palgrave Encyclopedia of Strategic Management*. Palgrave Macmillan: London, pp. 504–507.

Anderson, P. and M. L. Tushman (1990), 'Technological discontinuities and dominant design: a cyclical model of technological change,' *Administrative Science Quarterly*, **35**(December), 604–633.

Arora, A., A. Fosfuri and A. Gambardella (2001), 'Markets for technology and their implications for corporate strategy,' *Industrial and Corporate Change*, **10**(2), 419–451.

Audretsch, D. B., P. Houweling and A. R. Thurik (2004), 'Industry evolution: diversity, selection and the role of learning,' *International Small Business Journal*, **22**(4), 331–348.

Bakker, G. (2013), 'Money for nothing: how firms have financed R&D-projects since the Industrial Revolution,' *Research Policy*, **42**(10), 1793–1814.

Bloch, M. (1953), *The Historian's Craft*. Vintage Books: New York.

Cahoy, D. R., J. Gehman and Z. Lei (2013), 'Fracking patents: the emergence of patents as information-containment tools in shale drilling,' *Michigan Telecommunications & Technology Law Review*, **19**(2).

Christensen, C. (1997), *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Harvard Business Review Press: Boston, MA.

Clark, J. (1949), 'A hydraulic process for increasing the productivity of wells,' *Journal of Petroleum Technology*, **1**(01), 1–8.

Congressinoal Research Service (2015), 'Hydraulic Fracturing and Safe Drinking Water Act Regulatory Issues (R41760),' Washington, DC. https://crsreports.congress.gov/product/pdf/R/R41760, accessed November 1, 2022.

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

Crooks, E. (2014), 'Oil majors' R&D into conventional and renewable energy at risk: Fall in crude price puts pressure on long-term investments,' Financial Times: London. https://on.ft.com/41f77HI.
Economist (2013), 'Supermajordämmerung: The Day of the Huge Integrated International Oil Company is Drawing to a Close,' https://econ.st/3mlgXJx, accessed April 8, 2023.
Eggers, J. P. (2014), 'Competing technologies and industry evolution: The benefits of making mistakes in the flat panel display industry,' *Strategic Management Journal*, **35**(2), 159–178.
Engelder, T. (2014a), 'Major components of shale gas fracking technology", Inteviewed by R. Kapoor and J. P. Murmann on November 17'.
Engelder, T. (2014b), 'On the development of sale gas and fracking technology in U.S.A", Inteviewed by R. Kapoor and J. P. Murmann on August 12'.
Feiler, P. and D. Teece (2014), 'Case study, dynamic capabilities and upstream strategy: Supermajor EXP,' *Energy Strategy Reviews*, **3**, 14–20.
Fetter, T. R., A. L. Steck, C. Timmins and D. Wrenn (2020), 'Learning by viewing? Social learning, regulatory disclosure, and firm productivity in Shale Gas (revised version of 2018 paper)', National Bureau of Economic Research Working Paper Series, No. 25401.
Fisher, K. (2022), 'The evolution of fracking technology and the role of Mitchell", Inteviewed by R. Kapoor and J. P. Murmann on August 10'.
Floyd, F. R. (1949), 'Fracturing formations in wells,' United States patent application U.S.2596843A, https://patents.google.com/patent/U.S.2596843A/, accessed October 23, 2022.
Gaddis, J. L. (2002), *The Landscape of History: How Historians Map the Past*. Oxford University Press: New York.
Golden, J. M. and H. J. Wiseman (2014), 'The fracking revolution: shale gas as a case study in innovation policy,' *Emory LJ*, **64**, 955–1040.
Helfat, C. E. (1997), 'Know-how and asset complementarity and dynamic capability accumulation: the case of R&D,' *Strategic Management Journal*, **18**(*5*), 339–360.
House, K. E. (1997), 'Mideast 'Moderates'? Here we go again, Wall Street Journal, New York. https://www.wsj.com/articles/SB8727238592786605 00.
Joskow, P. L. (2015), 'The shale gas revolution: introduction,' *Economics of Energy & Environmental Policy*, **4**(1), 1–4.
Kapoor, R. and T. Klueter (2020), 'Progress and setbacks: the two faces of technology emergence,' *Research Policy*, **49**(1), 103874.
Kemp, J. (2014), 'The real shale revolution (July 14, 2014)', Reuters, https://reut.rs/3TRqR14, accessed March 12, 2022.
King, J. (1993), 'Drilling sideways—a review of horizontal well technology and its domestic application,' Washington: Energy Information Administration (ed.), U.S. Department of Energy. https://bit.ly/3TWQP3m, accessed October 30, 2022.
Levinthal, D. (1998), 'The slow pace of rapid technological change: gradualism and punctuation in technological change,' *Industrial and Corporate Change*, **7**(2), 217–248.
Manfreda, J. (2019), 'The real history of fracking', Oilprice.com. https://oilprice.com/Energy/Crude-Oil/The-Real-History-Of-Fracking.html, accessed January 6, 2019.
Mazzucato, M. (2015), *Entrepreneurial State: Debunking Public Vs. Private Sector Myths*. Anthem Press: Lnndon.
Mouawad, J. (2009), *Estimate Places Natural Gas Reserves 35% Higher*. New York Times: New York.
Murmann, J. P. (2003), *Knowledge and Competitive Advantage: The Coevolution of Firms, Technology, and National Institutions*. Cambridge University Press: New York.
Murmann, J. P. (2020), 'Historical methods in the social sciences: commentary on Schoemaker 2020,' *Futures & Foresight Science*, **2**(3–4), e55.
Murmann, J. P. and K. Frenken (2006), 'Toward a systematic framework for research on dominant designs, technological innovations, and industrial change,' *Research Policy*, **35**(7), 925–952.
Nelson, R. R. (1959), 'The simple economics of basic scientific research,' *The Journal of Political Economy*, **67**(3), 297–306.
Nelson, R. R. (1995), 'Why should managers be thinking about technology policy?' *Strategic Management Journal*, **16**(8), 581–588.
Ong, J. and R. Munson (2018), 'Hydraulic fracturing: A public-private R&D success story', https://bit.ly/3WsFo59, accessed October 31, 2022.
Perrons, R. K. (2014), 'How innovation and R&D happen in the upstream oil & gas industry: insights from a global survey,' *Journal of Petroleum Science and Engineering*, **124**, 301–312.
Platts Oilgram News (1999), 'Mitchell books 25% increase in gas reserves,' McGraw-Hill, Inc.
Roberts, E. A. L. (1865), 'Improvement in Exploding Torpedoes in Artesian Wells,' United States Patent Application U.S.47458A, https://patents.google.com/patent/U.S.47458A/en, accessed October 23, 2022

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024

Rosenthal, E. (2012), 'U.S. to be world's top oil producer in 5 years, report says', *New York Times*: New York.
Sasson, A. and A. Blomgren (2011), *Knowledge Based Oil and Gas Industry*. BI Norwegian Business School: Oslo.
Shuen, A., P. F. Feiler and D. J. Teece (2014), 'Dynamic capabilities in the upstream oil and gas sector: managing next generation competition,' *Energy Strategy Reviews*, **3**, 5–13.
Sidel, R. and C. Cummins (2001) 'Devon Energy to acquire Mitchell in $3.1 billion cash-and-stock deal,' *Wall Street Journal*.
Statista (2020), 'Leading shale oil producers based on daily average crude oil and condensate production in the United States in 2020, https://www.statista.com/statistics/1181897/oil-largest-shale-oil-producers/, accessed November 1, 2022.
Stern, F. R. (1973), *The Varieties of History: From Voltaire to the Present*. Vintage Books: New York.
Stigler, G. J. (1951), 'The division of labor is limited by the extent of the market,' *Journal of Political Economy*, **59**(3), 185–193.
Teece, D. J. (1980), 'Economics of scope and the scope of the enterprise,' *Journal of Economic Behavior & Organization*, **1**(3), 223–247.
Trembath, A. (2015), 'Shale Fracking Innovation Timeline,' The Breakthrough. https://bit.ly/3zqrI0A, accessed October 10, 2022.
Trembath, A., J. Jenkins and T. Nordhaus. (2012), 'U.S. Government Role in Shale Gas Fracking History: An Overview,' The Breakthrough Institute, https://bit.ly/3zqrI0A, accessed October 30, 2022.
U.S. Energy Information Administration (2000), 'International Energy Outlook 2000,' https://rosap.ntl.bts.gov/view/dot/5104/dot_5104_DS1.pdf, accessed May 3, 2023.
U.S. Energy Information Administration (2016), 'Most Natural Gas Production Growth is Expected to Come From Shale Gas and Tight Oil Plays,' Energy Today, https://www.eia.gov/todayinenergy/detail.php?id=26552, accessed October 31, 2022.
van der Eijk, J. (2020), 'Shell did not see the Shale gas revolution coming", Interviewed by J. P. Murmann on July 16'.
Wang, Z. and A. Krupnick (2015), 'A retrospective review of shale gas development in the United States: what led to the boom?' *Economics of Energy & Environmental Policy*, **4**(1), 5–18.
Wang, Z. and Q. Xue (2014), 'The market structure of shale gas drilling in the United States', Resources for the Future, Washington.
Wang, Z. and Q. Xue (2016), 'The market structure of shale gas drilling in the United States,' *Economics Bulletin*, **36**(2), 793–801.
Zuckerman, G. (2014), *The Frackers: The Outrageous inside Story of the New Billionaire Wildcatters*. Penguin: New York.

Downloaded from https://academic.oup.com/icc/article/33/1/106/7202170 by Universitat St Gallen user on 15 February 2024