Whose Frac is it, Anyway? Examining Intellectual Property of Hydraulic Fracturing to Explain Industrial Organization in Oilfield Services*

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Abstract

We analyze the relative roles in diffusion of knowledge that are played by sellers and buyers of hydraulic fracturing jobs. We provide evidence that sellers – oilfield service companies – actively disseminated knowledge in the form of both academic publications and patents. By contrast, buyers – oil and gas developers – contributed far less to sharing knowledge about hydraulic fracturing. While historically concentrated, the oilfield service sector experienced substantial entry following this dissemination of knowledge, with the result that initial leaders lost their advantage. These results have important implications for both sellers and buyers of technical services that are evolving and improving.

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1 Introduction

The emergence of hydraulic fracturing and closely related technologies – collectively known as fracking – was a profound technological change that ushered in a new era of oil and gas production. The change was not discrete, but the result of continual innovation aimed at improving and optimizing the extraction of oil and gas. With the emergence of fracking an important role emerged in the industry, which we refer to as the market for frac services or frac jobs. As in many markets, sellers in this market may be motivated to improve the quality and efficiency of their product or service. Such innovations may be managed in a variety of ways to extract value. For example, one might expect sellers to closely guard their techniques in an effort to capitalize the gains. Alternatively, firms might pursue strategies that seek to develop their reputation for talent and expertise. Buyers may also have had a motivation to improve their understanding of how the combination of ingredients impacts production.

As the fracking boom started in the early 21^{st} century, three firms were dominant sellers in the market for frac jobs.[1] By the end of the first decade of this century the three leading sellers had a combined market share of 75 percent (Rogers, 2011). Then, starting in 2010, public and political support swung towards requiring disclosure of frac additives out of concern about water contamination and public health. This disclosure operated slightly differently across states, but was largely coordinated through publication in the FracFocus database.[2] In many jurisdictions firms could avoid disclosing certain additives by invoking a clause protecting "trade secrets." An overwhelming majority of early disclosures took advantage of this loophole, effectively allowing firms to avoid disclosing certain parts of their frac recipes in the name of protecting proprietary individual additives. The pubic disclosure of ingredients used in frac jobs starting after 2010 allows systematic

[1] Sellers in this market are commonly referred to as oilfield service (or simply service) companies or pressure pumpers. To streamline the pursuant discussion we refer to such firms as "sellers." Buyers in the market for frac jobs are generally producers of oil and gas. We refer to these firms as "buyers."

[2] FracFocus was started in 2011 as a clearinghouse for information about the makeup of fracturing fluid. Wiseman (2012) provides a helpful background and discussion of the tradeoff between public and private efforts to promote disclosure. Several states use FracFocus as the official repository of disclosures in their states, while others allow firms to use FracFocus as a mechanism for disclosure. http://www.fracfocus.org

analysis of innovations in frac design and fluid chemistry.

An important policy point relates to the way we think about protecting or forcing dissemination of information about the ingredients used in a frac job. As Fetter et al. (2018) note, forcing disclosure of ingredients could adversely impact firms' incentives to innovate. On the other hand, if the sector from which these innovations are likely to emerge is highly concentrated, there is reason to be concerned that firms will withhold information so as to enhance any perceived product differences – thereby amplifying their market power. This analysis will likely be more complicated if there is a public concern about potential public health risks associated with some of the ingredients used in the process – particularly under conditions of secrecy. These observations raise a question: which side of the market – buyers or sellers – is the more important source of innovation? This is particularly relevant when the market concentration of buyers and sellers differs, as is the case in the market for frac jobs: oil and gas production is a highly competitive industry, so there were many potential consumers of frac services; by contrast, there is compelling evidence of market power on the seller's side.[3]

In this paper we evaluate the significance of intellectual property to buyers and sellers of frac jobs. We bring information from two novel channels of intentional dissemination of knowledge – patents and academic publications – to provide greater context for the management of IP and how it contributed to changes in the industrial organization of the sector. Both channels can signal knowledge and proficiency: A patent is an exclusive commercial right, but in order to receive that right the applicant needs to share specific and detailed information about the product, while a publication is intentionally sharing information with a broader audience. In the present application patents and publications were substitute mechanisms for diffusion of innovation, with sellers (particularly the largest sellers) relying on publications through 2015, and then dramatically switching to patents. We identify differential effects of IP for different types of firms (sellers vs. buyers) in contrast to previous results. We also document changing market structure for sellers

[3] One structural element that could support seller market power is uncertainty about attributes of frac jobs, which can make it harder for buyers to assess differences between buyers, thereby partially shielding those sellers from competition (as was true for many years in the beer and motor vehicle fuels industries during the 20^{th} century. As pointed out by an anonymous referee, uncertainty about attributes of frac jobs can also make it harder for buyers to capitalize on any valuable innovations they might develop.

(service companies) while structure of buyers (production) structure did not change. Our results have implications for any industry with technological gains that may be created by particular organizations but can be shared through contractual relationships.[4] They also speak to the deeper issue of the sharing of innovation and IP between buyers and sellers in vertical relationships. In our application, valuable rents from innovations in frac technology do not appear to have accrued to the beneficiaries of higher production – operators of producing wells – who saw no material change in an apparently competitive marketplace. By contrast, suppliers saw a substantial erosion of market power over time.

2 Intellectual Property Strategies

An innovative firm must choose how to manage its IP; if they do not, productive innovations are likely to spread to rivals and any advantage will be dissipated. Protection often boils down to choosing between patenting or relying on secrecy, relying on a combination of the two, or intentionally pursuing a strategy of diffusion (Hall et al., 2014). Patenting provides specific security and provides recourse in the event of infringement, but requires the firm to divulge detailed knowledge that could compromise the value of an innovation (Hegde et al., 2022). Some innovations may not be conducive to patenting – indeed, the greenest innovation in the past generation – allowing the displacement of relatively dirty coal for electricity generation – was not patented. Is there undue focus on patenting in the green energy literature, much like looking for a lost wallet under the streetlight? And what do we make of the emerging use of disclosure as a policy tool – do disclosure requirements stifle innovation, as Fetter et al. (2018) argue, or does it lead to increased innovation over time by virtue of increasing the public stock of knowledge?[5]

[4] While our application is in the oil and gas industry, this issue has application in other energy technologies, such as renewables, but also in other parts of the economy where intellectual property (IP) has a leading role (Hall et al., 2014).

[5] Johnson (2010) argues that innovation is promoted by enhancing this public stock, since such an increase amplifies what he refers to as the "adjacent possible" – the set of new possibilities linked to the current state of knowledge. Johnson's point is that innovations tend to come from tinkering with various combinations, generally including new combinations that are just outside the realm of current experience. He also argues that insulating current technologies from competition – while attractive to the proprietor of that knowledge – runs the risk of retarding the trajectory of innovation, including that of the firm's IP: "protecting ideas from copycats and competitors also

The possibility of unintentional diffusion by observing patents may restrict research efforts by the firm (Arora et al., 2021). Alternatively, it may make a firm resort to secrecy as an IP management strategy, and thereby avoid the required disclosure in the patenting process. Reliance on trade secret protection can increase firms' incentives to experiment, which could lead to more complex input combinations (Cunningham and Kapacinskaite, 2021).[6] On the other hand, secrets may be hard to maintain and offer no legal recourse if lost. Moreover, external concerns such as environmental issues can have a bearing on disclosure. For example, mandated disclosure of frac fluid and surface water quality measures in the neighborhood of oil and gas wells has been linked to improvements in water quality.[7] While this work does not account for changing inputs or practices in frac jobs per se, it provides further evidence that disclosure is a powerful concern affecting both firm behavior and spillovers to a broader population. Choices about IP management may have importance beyond the immediate scope of operations in the firm and industry.

2.1 Patents

Patenting is one option available to firms. Using patents as proxies for innovation and patent citations as proxies for knowledge diffusion has a distinguished precedent in economics (Popp, 2019). In measuring the pace and diffusion of technological advances, economists have often analyzed patents (MacGarvie, 2005; Johnstone et al., 2010; Moser, 2013). Using patent citations as a measure of the relative importance of patents was introduced by Albert et al. (1991), and confirmed to be correlated with underlying firm value by Hall et al. (2005). Benson and Magee (2015) show that increased patenting activity is a reliable indicator of technological progress across a number of industries, though patents are more likely to be used to protect new products rather than new techniques (Popp, 2019). The quality of

protects them from other ideas that might improve [those original ideas], might transform them from hints and hunches to true innovations" (Johnson, 2010, p. 124).

[6] Trade secrets may also enhance the firm's ability to "capture value from their projects increases because of increasing causal ambiguity", making it more difficult "for rivals to deduce the causal links between observed inputs and outputs" (Cunningham and Kapacinskaite, 2021, p. 13) – but then, of course, it also makes harder for *customers* to infer the quality of the firm's product.

[7] See Bonetti et al. (2023) for discussion. The water quality measures are primarily measures of salt concentrations, with improvement primarily along the dimension of reducing measured concentrations rather than the number of affected surface waters.

different patents is more difficult to measure, and may vary across different plausible measures (Higham et al., 2021). Relatedly, there are a variety of potential sources of patent data (Andrews, 2021).

Popp et al. (2020) analyze innovation in green energy, which they measure by patents (globally, and specifically in the US and EU). They observe that green patenting peaks between 2009 and 2011, several years before innovation in fracking peaks (which they argue occurred around 2014, though it worth noting that their time series only runs through 2015). They suggest this earlier peak in renewable innovation might have been due to redirection of R&D efforts into fossil fuels (Acemoglu et al., 2019) or because of a trend towards weaker regulations. Our analysis casts doubt on both of these explanations.

Viewing enactment of the 1999 American Inventor's Protection Act (AIPA) as a natural experiment, Hegde et al. (2022) consider patenting before and after AIPA, comparing behavior in the U.S. against foreign patenting behaving. The authors find that patent publication enhances knowledge diffusion, in part by facilitating rival inventions (as evidenced by rival patenting decisions). A key feature in AIPA was that it required patent applications filed on or after November 29, 2000 to be published 18 months after the application date (roughly a two-year reduction in the period before such disclosure occurred prior to AIPA), though applicants could avoid this stipulation under the condition that they forgo foreign protection. Only about 8 percent of applicants opt out of pre-grant publication – pointing to a preference for disclosure over secrecy for inventions in exchange for a chance at exclusivity. Notably, the "no disclosure" option was more likely to be exercised in "complex product" industries or by smaller firms (Graham and Hegde, 2015).

Originally patented in the late 1940s, hydraulic fracturing is a complex technique involving many inputs as well as processes that may be hard to replicate. In the more recent application of the technology in the 2000s, the previous patenting history and complexity of the process suggests that a portfolio of patents might be required to adequately protect the relevant IP. This is relevant given that patents have been identified as a potential constraint to more complete information about hydraulic fracturing Cahoy et al. (2012), particularly because of the reliance on experiential learning.

2.2 Trade Secrets

A second strategy that an innovator might pursue to protect its IP is to keep its new techniques secret. As disclosure is limited under this strategy, one way to learn about the use of trade secrets is to study other sources of reporting, such as R&D expenditures. Using this approach, Amore (2020) notes that policy uncertainty can influence firms' incentive to report key information. He also finds that larger firms are more likely to withhold information in this setting, and that policy regimes that better restrict knowledge appropriation (for example, non-compete clauses or stronger trade secret protection) reduce the tendency to withhold information in face of policy uncertainty. Png (2017) studies the role played by institutions that offer increased protection for trade secrets. He analyzes the impact of a state's adoption of the Uniform Trade Secrets Act (UTSA) as increased protection for trade secrets; since 40 states had enacted the UTSA by 2000, but at different times, he treats adoption as a quasi-random experiment. He finds that adoption of the UTSA exerted a "nuanced effect" on R&D, encouraging increased effort mostly in larger firms, and that the effect of adoption on firms operating in a single state is unimportant.

Regarding trade secrets as an alternative to patents as a means to capture value from R&D, Cunningham and Kapacinskaite (2021) argue that trade secret protection can increase tendency towards complexity and breadth of inputs, via increased tendency to experiment. They also argue that trade secrets can enhance a firm's profitability because such secrets can impede rival firms' ability to deduce the causal links between observed inputs and outputs.[8] The authors' empirical strategy is to use the enactment of the 2016 Defend Trade Secrets Act (DTSA) to investigate the management of IP relevant to hydraulic fracturing. They interpret the DTSA as a natural experiment in seven states who collectively represent the lion's share of fractured wells (Arkansas, Colorado, Louisiana, Oklahoma, Pennsylvania, Texas, and Wyoming.) The idea is that the DTSA should encourage enhanced experimentation and use of trade secrets exceptions. Because ingredients that are kept secret cannot be observed, the authors interpret secret invention indirectly. Expanded use of undisclosed chemicals that appear in categories that are new to the firm are considered innovations. They find that such activity does increase, which

[8] As we noted above, this also makes causal inference harder for potential customers.

they then interpret as evidence that projects become more innovative after the DTSA, at least in the dimension of fluid chemistry.

While innovation may be promoted by – particularly for large firms (Png, 2017) – legal treatment of secrecy may limit long-term diffusion and innovation in other ways (Johnson, 2010; Ganglmair and Reimers, 2019). Moreover, even with trade secret protections, there is a natural concern that former employees may capture some of the firm's intellectual property, in the form of enhanced human capital. This effect can mitigated to some degree by the use of non-compete clauses in workers' contracts (Amore, 2020). Such clauses can be a substitute for trade secrecy institutions (Png, 2017, p. 178).

2.3 Diffusion via Academic Publication

In addition to revealing techniques that are protected, patents can convey useful information to market participants. For example, by holding patents a firm might be signaling its abilities to buyers. Such information might be transmitted in other ways; for example a firm that actively publishes in well-regarded scholarly outlets might develop a reputation for relevant technical expertise, which it could subsequently capitalize on as it markets its services to potential buyers. Once published, an article identifies the identity and affiliation of the author(s). A reader can reasonably infer that a journal article reflects well on those who author the paper as well as the institute or company the author is affiliated with. In particular, it seems plausible that the journal's audience will regard a company that employs authors who share positive results related to fracking as innovative and productive. In this way, journal publications play a role that is similar to advertising: both provide an avenue for increasing the firm's reputation; both publications and advertising can be viewed as a signal of product quality.[9] Either action can signal

[9] Clark (2007); Clark et al. (2009) provides empirical analyses that ask whether advertising is "informative" or "persuasive." Informative advertising "should help overcome perceived product differentiation and so should lead to price competition and lower prices"; persuasive advertising would raise "the perception that there are fewer substitutes for promoted brands and thus increases perceived differentiation and prices" (Clark, 2007, p. 758). He finds that market shares of larger (established) firms are higher when advertising is regulated and that prices are higher in the regulated region than elsewhere. In the context of disclosure regulations for frac jobs that allow withholding information about ingredients, this raises the possibility that such regulations insulate larger firms from erosion of perceived product differentiation.

quality so long as higher-quality (*i.e.*, more productive) firms think they will receive a greater payoff from the action than will lower-quality firms.

Popp (2016) investigates this potential for information transmission, asking what role publications played in the sequence from R&D spending on energy innovations supported by government monies through publication to patenting. To this end, he measures the impact of a publication by the number of citations received in a subsequent patent application. In the context of green innovations (*e.g.*, biofuels, solar, and wind) his results point to a significant lag between publication and related patenting.[10] In such an event, publication could be a faster way to enhance the firm's profits – trading off the longer term gains from holding a patent for the more immediate benefits of an enhanced reputation. Working in the other direction, publications may reveal certain pieces of information to potential competitors.

2.4 Learning

Technical diffusion can occur through multiple pathways. Firms can acquire and develop knowledge as they gain experience, a pathway often referred to as learning by doing or experiential learning; learning as a result of private knowledge made public, via knowledge spillovers; diffusion via embodied human capital that moves through the industry; and diffusion via publicly-intended knowledge.

2.4.1 Learning by doing

The first channel can manifest via an individual firm's aggregated experience, or via interactions with other firms (what Tang (2018) refers to as "learning by interaction," which she argues played a particularly important role in the pattern of technological change in wind energy).[11] Learning by doing has been recognized as a significant phenomenon in a range of manufacturing industries, from shipbuilding (Thompson, 2001) and aircraft manufacture (Alchian, 1963) to semiconductors (Irwin and Klenow, 1994). The broad observation of evolution of oil and gas production towards a manufacturing model exploiting unconventional resources (Newell et al., 2019) lends credence to the application of learning-by-doing in this

[10] Popp argues this lag could be as large as 8 years.

[11] Partnerships between operators and service companies may be less about specific knowledge or relationship-specific knowledge and more about match quality (Nagypál, 2007).

setting. A substantial literature has built up around identifying experiential gains from oil and gas production in general, and hydraulic fracturing in particular (Kellogg, 2011; Covert, 2015; Fitzgerald, 2015; Fukui et al., 2017).

2.4.2 Learning by viewing

The second channel captures the idea that publicly available information can be used by any market participant, not just the firm that is the source of this information. Within this channel, ideas developed by one firm are then mimicked or adapted by another. Fetter et al. (2018) focuses on this channel, arguing that the increased use of reporting regulations in states where fracking is important provides an avenue for information dissemination. Studying the reported combinations of ingredients in frac jobs in Pennsylvania, these authors argue that learning has led firms to use very similar combinations of ingredients over time, which they interpret as evidence that learning has lead to convergence. This channel could also manifest when firms learn where to direct efforts to develop resources, for example via exploration (Agerton, 2020; Steck, 2022; Hodgson, 2021; Covert and Sweeney, 2022). One issue that arises here is the pace at which useful information from exploratory efforts becomes publicly available; if such information becomes widely known, then the learning-by-viewing channel seems most appropriate for describing the phenomenon; in this case, the information takes on a public good characteristic, raising the possibility of too little effort obtaining. But if information disseminates less rapidly, then firms may be able to capitalize on that information, for example by speculating in related markets (Mason, 1989; Wang and Krupnick, 2013); in this case too much exploratory effort could obtain.

2.4.3 Learning via mobile human capital

As information accrues from experience, firms will develop expertise. But those executing the operation may also learn, *i.e.*, they may experience increases in their job-specific human capital. These intangible assets travel with the individual, so were that person to relocate to a different market participant they would take their accrued expertise with them, leading to the opportunity for the new employer to capitalize in part on the original firm's experience. This embodied human capital and experience could move with former employees either horizontally or vertically within the industry, to existing or new companies. It could also exit the industry, creating a "brain drain" observed in some industries, including oil and gas, especially during booms and busts (Rickman et al., 2017).

Png (2017) is mindful of this possible avenue, suggesting that trade secrecy can be a complement to "covenant not to compete" (CNC) clauses in employment contracts. Less clear is how such clauses would operate were the individual to relocate from a seller in the market for frac jobs to a buyer in that market, perhaps as a result of the buyer's interest in developing in-house capabilities. Thus, it seems a case could be made that CNC clauses could be tricky to deploy in the market for oilfield services, and this channel for diffusion deserves further attention.

2.4.4 Learning from other forms of publicly available information

As we noted above, firms may be drawn to sponsor academic publications as a way to signal their expanding expertise in techniques relevant to their market – presumably to buyers of such services. The flip side of such ventures is that the publications can contain information of potential value to other sellers. We focus on the related channel of diffusion of knowledge through involuntary or required disclosure in the discussion below.

3 Background Information

3.1 Data

Data for the empirical analysis are from several sources, as described briefly here and in greater detail in Appendix A. We collected data on 6,224 patents related to "hydraulic fracturing" that the U.S. Patent and Trademark Office issued between 2000 and 2019. These data included both patents by the applicant and assignments to another entity. Data on frac jobs is provided by Primary Vision, a commercial data supplier. The data provide detailed information on over 165,000 frac jobs. The study period begins in January 2011 and ends in December 2019, thereby avoiding any concerns about the covid pandemic and its attendant effect on oil and gas markets. The Primary Vision data include information about frac jobs with undisclosed, or secret, dimensions. Production data for the wells that were provided by Enverus, allowing for a direct link between the characteristics of the frac performed on each well and the production outcomes.

Market shares in the market for frac services were derived from the Primary Vision data, not accounting for mergers and acquisitions over time. Market shares were calculated at different levels of spatial and temporal aggregation using the Herfindahl-Hirschmann Index (HHI), which takes a value of 10,000 if a single firm controls the market; a typical threshold for concerns about market power is an HHI of 2500. HHIs are not affected by ignoring mergers and acquisitions, but knowledge embodied within organizations may not be fully represented.

A novel contribution of our paper is to extend the analysis of intentional disclosures to academic publications. A natural outlet that could attract such publication activities is the *Journal of Petroleum Technology* (JPT). This outlet has a solid reputation among both researchers and practitioners, as evidenced by its high impact factor. Their readership is technically attuned to the oil and gas industry and might reasonably be expected to keep abreast of new ideas and developments by reading the latest articles. We identified 18,959 papers related to “hydraulic fracturing” published between 2000–2019.

3.2 Market Structure in Oilfield Services

Fetter et al. (2018) underscore the competitive nature of the industry in Pennsylvania, both for buyers and sellers of frac jobs. Our analysis of market concentration as measured by the HHI in Table 1 indicates that there is greater scope for local market power than there is nationally, and far more potential market power in oilfield services than in oil and gas production itself. Oil and gas producers can expect a competitive landscape no matter where they locate across the U.S. Furthermore, any individual U.S. producer is tiny in the context of global oil and natural markets. Oilfield services exhibits a much higher HHI, even approaching levels traditionally regarded as reflecting market power. This suggests that sellers may have more power than buyers in this context.

Table 1 shows a change in the market concentration for sellers but not for buyers. The oilfield service sector is a large and diverse collection of firms that was historically dominated by three large sellers (Baker Hughes, Halliburton, and

Schlumberger); these firms' combined market share was 75% as recently as 2011 (Rogers, 2011).[12] Platt and Platt (1989) showed the strong interrelationship between buyers and sellers of frac jobs—not surprising given that the service industry relies on upstream investment by developers. Such a setting is an ideal venue for charging high markups to capitalize on specific knowledge, even if doing so is not sustainable in the long term. However, during the five year period between 2015 and 2020 substantial entry occurred, dramatically changing the industry (Crompton, 2020). Even more striking, each of these three historically dominant sellers – all of whom played an outsized role in the disclosure of innovations over time – have either partially or wholly exited the market.

3.3 Technological Diffusion

Fracturing jobs are complicated, with dozens of possible ingredients and many measurable characteristics; this leads to a huge number of potential configurations in frac recipes. To break that curse of dimensionality Fetter et al. (2018) used a Jaccard index to directly compare the similarity of different jobs on a unit interval. A Jaccard score of 1 means that two wells have identical components while a score of 0 means they have no components in common. Figure B.1 in the Appendix depicts the smoothed distribution of these scores for wells with the same or different operators for 4,944 wells in Pennsylvania. While the same operator distribution first-order stochastically dominates the different operator distribution, there is considerable overlap – leading the authors to conclude that frac jobs in Pennsylvania are becoming ever-more similar over time.

Using the same method on a sample of 352 wells fractured during a somewhat different time period in Wyoming, Fitzgerald and Mason (2021) found a different pattern than that depicted in Fetter et al. (2018) (cf. figure B.2 in the Appendix). This contrast suggests that diffusion incentives may differ over time and space.

While this sample does not have as many wells as the entire state of Pennsylvania, a longer period of experience with unconventional wells may have given firms participating in Wyoming more time to refine its frac recipe. A second possibility is

[12] Indeed, one motivation for early innovation in hydraulic fracturing was the high markups on gels – a key ingredient in frac jobs; gels were furnished by service companies at markups as high as 1000 percent (Steffy, 2019).

that there are fewer or smaller relevant differences in the geology across one county than there are across a state. One reason for slightly different frac recipes across Pennsylvania is that the geology may differ slightly, requiring different recipes to maximize well productivity. A third explanation could have to do with the structure of the industry, which is more concentrated in Wyoming – facilitating heterogeneity in the products provided by sellers.

3.3.1 Patents

As Figure 1 illustrates, patenting activity between 2000 and 2019 was nearly exclusively attributable to sellers (service companies). This is a striking finding, indicating that sellers regarded patents as an important component of IP management in a way that buyers did not. It is also notable how little patenting activity there was in the key years of propagation of fracking throughout the United States. Indeed, as fracking expanded throughout the United States between 2000 and 2010 only 1,315 patents related to hydraulic fracturing were granted. Moreover, the lion's share of patenting activity prior to 2015 was tied to acquisition of patents. This relatively low level of patenting activity during the period where fracking witnessed its fastest expansion stands in contrast to conclusions about patenting for fracking discussed in Popp (2019) and Acemoglu et al. (2019).

3.3.2 Publications

For each of the JPT papers related to fracking between 2000 and 2019, we identify the list of authors along with the affiliation reported for each co-author. This allows us to identify those papers co-authored by an employee of a seller (*i.e.*, oil service firm) or a buyer (*i.e.*, an oil and gas operator). The pattern of JPT publications over this time period is illustrated in Figure 2. Similar to patents, publications are concentrated amongst sellers.[13] Moreover, much of the publication activity by sellers can be linked to large firms, as Figure 3 illustrates. This figure displays the time series of both JPT articles and granted patents over time, splitting out the large sellers from other sellers. While smaller firms were associated with some publication activity, larger firms accounted for substantially greater numbers of articles. While most apparent after 2010, large firms were still more prolific

[13] This figure effectively counts each author as equal. We consider a variant that assigns a weight to each co-author in inverse proportion to the total number of authors below.

publishers before 2010 – particularly between 2005 and 2010. (2010 is a notable point in time here, as it marks the period when public disclosure began). One interpretation of this pattern is that academic publications may have served as a sort of informational marketing channel, signaling competency and innovation to potential buyers – akin to a form of advertising.

The figure also shows that large sellers also accounted for the lion's share of patents after 2015 (when patenting became more wide-spread). Interestingly, while JPT publications increased steadily from 2000 to 2015 publications reversed after 2015 – about the time patenting became more widely observed. This suggests a shift from publication to patenting, particularly for the large sellers. Apparently, whatever value sellers saw in publications declined in relative terms over time. This could be evidence that an intellectual property edge dissipated, or that the advertising had the simultaneous effect of boosting rivals. This would be consistent with a story of "cutting one's own throat" through self-promotion.

The first column of Table 2 identifies different categories of affiliations of authors of the publications we observe. The second column counts the total number of papers published by *any* author reporting that affiliation. Co-authorship across affiliation types accounts for why there were more papers by affiliation than total number of papers. The third column tabulates *all* authorships by affiliation. One interpretation of the total is that the mean paper has 72,966/18,959 = 3.85 coauthors. The affiliation categories correspond to buyers (specialized contractors, independent operators, major operators, national oil companies), sellers (service companies), and other affiliations (including academic researcher). In addition, some authors do not identify an affiliation, and others are not easily classified. What jumps out of Table 2 is that sellers of frac jobs are a leading supplier of academic publications. In contrast, buyers of frac jobs contribute only minimally to JPT publications.

Other types of affiliations exhibit time-invariant patterns in the data. Table 3 gives a detailed classification of publication and patenting activity across different types of organizations. First, independent producers, who drill most of the wells in the United States, have not and do not invest much into research publication. Larger operators, including major integrated oil companies, have larger research departments and expert geology and engineering staffs, so it is not surprising that they contribute, even though they drill fewer wells. National oil companies, which largely do not employ hydraulic fracturing, are similarly equipped with technically-proficient personnel who can contribute to the scientific literature. A substantial fraction of authors and publications emanate from places not otherwise classified. Some authors come from major corporations with substantial research expenditures, while many others come from boutique consultancies or other opaque organizations. Many of these affiliations are individually responsible for only a handful of authorships.

3.3.3 Secrecy

In the initial period of disclosure, over 80 percent of fractured wells invoked a trade secret; Figure 4 illustrates. Evidently, faced with the prospect of disclosure due to state laws and ultimately the FracFocus registry in 2011, firms initially tried to shield parts of their activity. But as the number of wells fractured each quarter grew and remained high between 2012 and 2015, the share of jobs invoking trade secrets fell substantially – indeed, secrecy was rare by the end of 2014. Konschnik and Dayalu (2016) conclude that systems approaches to reporting reduce the incidence of withholding information.[14]

Combining the messages from Figures 3 and 4, it appears that rather than relying exclusively on trade secrecy, larger sellers were content to disclose some details of their innovations via publications, perhaps hoping that such publications could attract the interest of potential buyers. After 2014, however, there seems to have been a switch to a patenting strategy.

4 Empirical Analysis

We analyze the empirical record to link the diffusion of technological innovation to changes in production and ultimately industry structure. This is a complicated process with several outcomes that are evolving and affecting one another. Most of

[14] For a review of the standards for legal recognition of trade secrets see Wiseman (2011). The widespread reliance on secrecy raises the question of whether more secretive fracs are more productive. Fitzgerald and Mason (2021) found that secrecy was concentrated in certain parts of the frac fluid, and that these secret ingredients were not systematically used in higher-producing wells.

our analysis is limited to the period since 2011, when detailed hydraulic fracturing data became available thanks to disclosure requirements like FracFocus. Aggregate data from Gallegos and Varela (2015) show that the prior decade was a period of rapid adoption of hydraulic fracturing, and it is likely that many innovations were made during that period. We are not able to link innovation and market structure in that period with currently available data. However, since 2011 we are able to study the empirical relationships between production, intentional diffusion of knowledge, and market structures.

4.1 Production and Knowledge Dissemination

The first issue we explore is whether information dissemination exerts a positive effect on a firm's performance. To this end, we examine whether measures of innovation are likely to lead to higher well production. Innovations, such as patents or publications, are observed at the company level. We assess the potential impact from innovations, allowing for both recent (flow) and lingering (stock) effects. Both are measured for the preceding quarter, which we assume captures the market impression of innovativeness associated with a particular firm (or member of the 'other' firms). We capture the stock impact via cumulative numbers.[15]

We consider four measures of information dissemination: patents granted to the firm; patents acquired by the firm (generally, acquired from some other commercial entity); JPT articles where a co-author is affiliated with the firm; and JPT articles weighted by citation count (intended to give a sense as to the apparent importance of the article). We implicitly assume that all innovations attributable to a given company are relevant to any activities undertaken by the firm anywhere in the US.[16] In light of the potential tension between innovation and secrecy, we also include a measure of secrecy in this analysis. This measure is a simple count: in any period, for any firm, we add up the number of wells for which there is at least one ingredient in the frac job (whose identity is not reported (*i.e.*, that is held secret). We assess the role of innovations and secrecy separately for buyers and sellers. We

[15] One imagines there could be some sort of depreciation in these effects, which might render the recent values more salient than the stock values. Allowing for such differences is a key motivation in our modeling choice to include both flow and stock effects.

[16] For example, an academic publication about operations in Texas is treated as influencing production nationwide rather than just for wells in Texas.

allow for firm-specific effects, along with idiosyncratic temporal effects. Finally, we include price as a regressor.

Our empirical approach is to exploit differences in the timing and accumulation of innovation across firms over time to determine the underlying relationship with production. Equation 1 expresses our estimating equation for sellers:

$$\begin{aligned} log(PROD)_{ik} &= \alpha_1 INNOV^f_{1k-1} + \alpha_2 INNOV^f_{2k-1} + \alpha_o INNOV^f_{ok-1} \\ &+\beta_1 INNOV^s_{1k-1} + \beta_2 INNOV^s_{2k-1} + \beta_o INNOV^s_{ok-1} + \gamma P_k + \mu_i + \nu_{kt} + \varepsilon_{ik}. \end{aligned} \tag{1}$$

In this equation $log(PROD)_{ik}$ is the natural log of production – measured in barrels of oil equivalent – during the first 12 months of production for wells fractured by company i in quarter k.[17] We denote the flow of innovative effort (*i.e.*, actions from the preceding quarter) by "INNOV^f" and the stock of innovative effort (*i.e.*, cumulated actions as of the preceding quarter) by "INNOV^s"; the roles of these measures are evaluated for each of the four measures of innovation. Here, the subscript '1' refers to seller Schlumberger and the subscript '2' refers to the seller Halliburton; these were the two largest sellers in the market for frac services.[18] The subscript 'o' refers to all other sellers. P_k refers to the market price in quarter k, taken as the West Texas Intermediate spot price of crude.[19] Finally, μ_i is a firm-specific fixed effect for seller i and ν_{kt} is an indicator variable that equals 1 for the year t in which quarter k is included. The estimating equation for buyers is quite similar, with distinction that neither Schlumberger nor Halliburton are buyers of frac jobs and so we drop the terms sub-scripted by 1 or 2; accordingly, the terms subscripted by "o" in this regression equation refer to all buyers, and the firm-specific fixed effect is tied to buyer identity.

In Tables 4 and 5 we present regression results based on this estimating equation. Table 4 provides these results for sellers, while Table 5 provides results for buyers. In both tables, regression 1 reports results based on the "patent applications"

[17] Several other possible production measures could be substituted here, but Mason and Roberts (2018) showed that the first 12 month measure performs well against alternatives.

[18] The third large seller, Baker Hughes, was generally inactive in each of these methods.

[19] This price is the average spot price during the quarter in question. There is some controversy as to whether futures price would be a more suitable measure here; for example, Alquist and Kilian (2010) arguing against the use of futures price and Ellwanger and Snudden (2023) arguing in favor of the use of futures prices. Conceptually, one expects the two prices to be linked.

measure of IP; regression 2 reports results based on the the "patent assigned" measure of IP; regression 3 reports results based on the "articles authored" measure of IP; and regression 4 reports results based on the "weighted citations" measure of IP. (The latter two are tied to JPT publications; the authorship measure counts the number of articles authored by an employee of the firm in question, while the weighted citations count pro-rates the count by the number of co-authors).

The results reported in Table 4 indicate that IP plays an important role in explaining productivity of the two large firms, with the cumulative IP measure exerting a positive and statistically significant effect in each of regressions 1, 3 and 4 for both Schlumberger and Halliburton. For regression 2, recent activity is statistically important for these two firms but cumulative activity is not. One interpretation of these results is that measures 1, 3 and 4 are more closely tied to the firm's own efforts, and hence may deliver a more compelling signal of its productive capabilities, while measure 2 is linked to entrepreneurial activity (hunting for and acquiring new patents). In any event, taken as a whole, these results are consistent with the notion that IP is particularly important for the two large firms. For other firms, the cumulative measures are all statistically important but the effect is negative; this could indicate that efforts directed at developing IP substitute away from other actions that contribute to productivity. To the extent this is the case, it would seem that smaller firms lack the resources to successfully engage in developing IP and enhancing productivity. We also see that secret wells are unimportant in explaining productivity in each regression, calling into question the idea that withholding ingredients protects valuable trade secrets. Finally, we see that price exerts a significant positive impact on productivity, both statistically and economically, consistent with an upward-sloping supply curve for frac jobs.[20]

The results reported in Table 5, in contrast, do not provide compelling evidence that buyers (*i.e.*, oil and gas operators) can enhance well productivity by developing IP. For each of the four measures the cumulative IP measure is either statistically unimportant (regressions 4) or exerts a negative effect (regressions 1, 2 and 3). This latter aspect is akin to the features for "other sellers" reports in the preceding table, in that increased cumulative effort appears to come at the expense of increased

[20] This aspect of our analysis is similar to results in Newell and Prest (2019), who argue that drilling is relatively responsive to price. Their analysis focuses on market effects, as opposed to our focus on firm-specific effects.

productivity. Recent patent measures, however, are positively correlated with buyer productivity. The importance of this result is somewhat diminished by the small role buyers played in both patent applications and patent assignment, as reported earlier in the paper. As with the results for sellers, we also see that secret wells are unimportant in explaining productivity in each regression; as above, this casts doubt on the premise that withholding ingredients protects valuable trade secrets. Finally, we see that price exerts a statistically unimportant role on production. This might reflect the idea that well-level production is often driven by physical forces (*e.g.*, decline curve effects), and accordingly is highly unresponsive to price, which has been proposed in recent empirical work (Anderson et al., 2018; Mason and Roberts, 2018).

4.2 Knowledge Dissemination and Market Structures

We next investigate the relationship between productivity and market structure. Here, we are ultimately interested in the evolution of market power for different firms. In this regard we analyze firms' market shares, interpreted as the fraction of wells drilled in a particular period on the relevant side of the market. That is, we study separately the pattern of market shares for sellers and buyers.

We start by assessing the influence of firms' productivity upon market share. All else equal, one expects more productive firms to command a larger market share, and so we estimate the following panel regression:

$$SHARE_{ik} = \alpha log(PROD)_{ik} + \beta SECRET_{ik} + \gamma_{kt} + \varepsilon_{it}, \tag{2}$$

where $SHARE_{it}$ represents the ratio of the total number of wells drilled by firm i in quarter k to the total number drilled in the country as a whole.[21] As above, $log(PROD)_{ik}$ is the natural log of production during the first 12 months of production for wells fractured by company i in quarter k, measured in barrels of oil equivalent. Also as above, γ_{kt} is an indicator variable equaling 1 for quarters k in year t. In addition, we include a variable measuring the number of newly drilled wells associated with firm i in quarter k that contain at least one ingredient whose identity is withheld, denoted as $SECRET_{ik}$. We include this variable to capture the

[21] While sub-markets with greater amounts of concentration are evident, the non-rivalry of information leads us to consider the aggregate national market.

potential effect of proprietary information upon market share. Such withholding behavior could enhance a seller's position by increasing its ability to claim special ability, as we noted above. Alternatively, proprietary information might help enhance the firms efficiency, as others have proposed. We estimate the specification in this equation separately for operators and service companies.

Results from these regressions are reported in Table 6. The first column of results reports estimates for buyers while the second column reports estimates for sellers. For both sides of the market we find evidence that higher average productivity is correlated with higher market share, though the effect is substantially greater for sellers. We also find that a positive effect associated with secrecy. The interpretation of the estimated values is that a 1 point increase in the log average productivity for the firm in the 12 months prior to drilling the well is associated with a modest increase in market share (.09%) for buyers, with a somewhat larger impact (.62%) for sellers. Similarly, adding a well with a secret ingredient delivers a modest increase in market share (.06% for buyers and .07% for sellers).

In evaluating these results, it is worth noting the potential for simultaneous equation bias in the regression equation (2). One can imagine sellers with larger market share attracting clients with more promising drilling prospects – in which case larger share could increase the firm's measure of productivity. For buyers, it is conceivable that firms with larger market shares are better situated to win attractive drilling concessions (*e.g.*, by having deeper pockets in auctions), again suggesting larger productivity for firms with larger market shares. To the extent there is inertia in market shares (firms with larger market shares retain that position of dominance for consecutive periods) this raises the potential for correlation between the residual in eq. (2) and $PROD_{ik}$.

One can address this potential simultaneity bias via an instrumental variables (IV) approach. In such an approach, one proposes a set of variables thought to be correlated with the potential endogenous right-side variable, here $PROD_{ik}$, and exploits the fitted values from that relation in the original regression equation. Reflecting on the results obtained reported in Tables 4 and 5, we use the four measures of contemporaneous innovation, along with the spot price of crude oil, as instruments for productivity. The results from such an IV approach are reported in Table 7.

We note first that this regression model passes standard tests for strength of instruments.[22] The result confirms that production is statistically important to sellers, with a one-unit increase in log average productivity raising a firm's market share by 11.45%. By contrast, the IV results indicate a lack of statistical importance for productivity in driving market share for buyers. Secrecy, on the other hand, has a more muted effect for sellers (with the point estimate reaching statistical significance at only the 10% level).

One way to think about the line of reasoning in this subsection is as follows: we show in subsection 4.1 that innovations are associated with increased production for sellers (though to a lesser extent for buyers). To the extent that such production increases are then manifested in increased market share, there is a tangible benefit from innovation via this two-step chain (innovation driving increased output, which subsequently raises market share). While allowing for reverse causality undercuts any relation for buyers – casting doubt on potential gains to buyers from innovation – it does not do so for sellers.

5 Discussion

So whose frac is it, anyway? Do buyers (operators) or sellers (service companies) deserve the lion's share of the credit for innovations in hydraulic fracturing? The results we documented above point to sellers as playing the more important role. These firms, and in particular the three largest service companies, produced a substantially larger number of the publications and patents related to fracking than did operators. The early reliance on publications as a means of establishing expertise, rather than patenting any new discoveries, was generally combined with a reliance on trade secrets. The strategies sellers employed to memorialize innovations changed over time as the industrial structure also evolved.

While particularly important and much more prevalent during the earlier period we study, the use of trade secrets was important throughout; indeed, its usage increased in 2017–18 relative to 2014–15 (Cunningham and Kapacinskaite, 2021). This in turn suggests that there was a pivot back towards secrecy after 2016 even as service

[22] Specifically, the first stage F statistic is sufficiently large to lend credibility to the chosen instruments, while the potential for over-identification can safely be dismissed (the Hansen test statistic for the hypothesis of everidentification is well below statistically significant levels).

companies tried to simultaneously patent and otherwise protect IP – painting a picture of firms scrambling to take any measures available in the face of stiffer competition.

A related phenomenon that merits some consideration has to do with the evolution of the market for frac services. Despite the impressive dominance of the big 3 service companies in the early 21^{st} century, with an overwhelming share of the market in 2011, in the following decade these erstwhile dominant firms not only managed to lose their grip on a lucrative market, but were compelled to exit that market in part or entirely. New entrants often specialized in a narrow suite of oilfield services around pressure pumping, which corresponds most closely to specializing in frac jobs. One possibility is that this exit was the result of market shakeup following the collapse in oil prices in the middle of this decade. While this explanation may have some relevance, the results we report in – which include both market price and annual fixed effects as explanatory variables, and which highlight two of the large three sellers – suggest other forces were likely at play. One possibility is that an interesting, presumably unintended, consequence of the publishing activity by these large firms before 2015 is that changes in the industry structure in oilfield services then followed, with increasing competition as expertise diffused across the sector and through the industry.

If service companies were well-positioned to provide expertise as fracking spread, why did they not patent earlier? One answer is that these firms worried about the disclosure that would come with patenting, and so relied on publications as a means to signal their abilities – while maintaining secrecy to the extent possible. But that secrecy ultimately engendered a public backlash, ultimately leading to the adoption of public disclosure requirements. So why not switch to patenting earlier, when public disclosure became a real threat? Perhaps firms thought they could foil public disclosure or would not be able to sufficiently capitalize on patents at that time. Their change of heart three short years later casts doubt on the merits of this logic. In any event, it is clear that the later pivot to patenting came too late, much like trying to shut the gate after the proverbial cow was already gone.

Given the importance of fracking to energy and environmental policy, investigation of the forces influencing innovative efforts is instructive. The emergence of hydraulic fracturing relied on continual innovation, which could emerge from both buyers and sellers – with market participants having differing views of the resulting IP, and appropriate policy related to that IP, depending on whether they were a buyer or a seller. Adopting the gains from fracking could naturally benefit from experimentation and innovation by either buyers and sellers, depending on the institutional settings in their local market. Understanding the interplay of these factors helps explain why the United States was the birthplace of the shale revolution and its attendant welfare gains, by allowing for learning by building on the uniquely American legacy of fostering innovation (Khan, 2020).

The particular nature of hydraulic fracturing technology is relevant to this discussion. Fracturing recipes and processes differ with geological characteristics; a formula that stimulates production in one formation might be less successful in another. Large firms that operate in multiple geological basins recognize this reality. Patent protection is national, providing far more exclusivity than necessary for innovations with limited local applicability. Given the high costs of patenting, secrecy might be a more economical option for managing a valuable innovation. To determine the optimal strategy for IP management, one would have to understand the distribution of elasticities of production to fracturing inputs and innovation within and across different regions. The relatively high costs of patenting require that particular frac innovations be widely applicable and productive to warrant the investment.

Ultimately, profits are the objective of both buyers and sellers. These profits are difficult to observe. Both Covert (2015) and Steck (2022) try to relate changes in production technology to productivity by examining operator's costs – and ultimately profits. But this strategy misses the profits of sellers of frac services and therefore serves as a lower bound for the productivity gains. Over time, as innovations dispersed through the industry, it is possible that a combination of vertical integration (in-house provision of frac services by operators) and growing competitiveness in oilfield services, consumer welfare gains likely increased. These missing slices of economic welfare are important to consider, as a review of IP management illustrates that operators were not likely to own all relevant IP and had to pay markups to access new technologies.

6 Conclusion

Widespread adoption of hydraulic fracturing has delivered substantial environmental benefits by lowering natural gas prices and allowing coal-to-gas switching (Fell and Kaffine, 2018; Mason et al., 2015). Importantly, substantial innovation occurred before significant patenting activity emerged in the mid 2010s. Earlier patenting may have precluded rapid diffusion and adoption and the attendant welfare gains.

Firms are motivated to innovate when they anticipate earning large enough profits to rationalize the up-front costs of R&D. In turn, this depends on the firm anticipating a sufficiently large level of trade for a sufficiently long period of time. This will be more likely for firms with a greater share of the market, as with the three largest sellers in the oil service market, and less likely for small players, be they buyers or sellers. Further, these net gains will likely be enhanced by either patent or trade secret protection. Reporting requirements, as were common in the regulatory regimes that started to appear after 2011, complicate the ability to capitalize on the fruits of innovative efforts. An additional complication arises for those firms that operate in multiple regulatory venues, for example multiple states with distinct reporting requirements.[23]

Because hydraulic fracturing is a setting in which a new technology was developed and refined through learning by both sellers and buyers, we study the connection between the strategic choices about sharing innovations by firms and the changes in the structure of the industry. In this setting the sellers of the technology are oilfield service companies while the buyers are oil and gas producers.

We find significant difference between the IP management strategies associated with buyers (oil and gas operators) and sellers (oil service companies), with sellers much more likely to both protect and disseminate innovations. This suggests that sellers had a previously under-appreciated role in innovation around fracturing. Ultimately the innovations were broadly shared throughout the industry and the structure of

[23] One imagines that anything reported in state A could be mimicked by a firm's competitor in state B. An innovative multi-state firm could therefore be motivated to limit its operations in a venue with more strident reporting requirement, so as to protect its IP in other states. This could explain the comparatively small market concentration of oil service firms in Pennsylvania, whose reporting requirements are more demanding than most oil and gas producing states. In particular, the three large service companies have a relatively modest presence in that state.

the oilfield services sector became more competitive. Some of the dissemination through the industry can be attributed to service companies decisions to use disclosure as an IP management strategy, perhaps by using it as a kind of advertising to signal technical proficiency to potential buyers. Accounting for differing incentives in vertical relationships can provide valuable insight into technological diffusion and adoption.

While the pricing of oilfield services cannot be observed at a granular level, Sweeting et al. (2022) present a theoretical model of price competition in a setting in which there is learning and technical diffusion between sellers and buyers that we expect would be close to the setting we study. Their key prediction is that long-run equilibria are more likely to be competitive as knowledge disseminates, which is consistent with what we observe in the oilfield services market over time.

References

Acemoglu, D., Aghion, P., Barrage, L. and Hémous, D. (2019). Climate Change, Directed Innovation, and Energy Transition: The Long-Run Consequences of the Shale Gas Revolution, *Working paper*.

Agerton, M. (2020). Learning Where to Drill: Drilling Decisions and Geological Quality in the Haynesville Shale, *Working Paper 20-439*, USAEE.

Albert, M. B., Avery, D., Narin, F. and McAllister, P. (1991). Direct Validation of Citation Counts as Indicators of Industrially Important Patents, *Research Policy* **20**(3): 251–259.

Alchian, A. (1963). Reliability of Progress Curves in Airframe Production, *Econometrica: Journal of the Econometric Society* pp. 679–693.

Alquist, R. and Kilian, L. (2010). What Do We Learn from the Price of Crude Oil Futures?, *Journal of Applied Econometrics* **25**(4): 539–573.

Amore, M. D. (2020). Innovation Disclosure in Times of Uncertainty, *Journal of Economics & Management Strategy* **29**(4): 792 – 815.

Anderson, S. T., Kellogg, R. and Salant, S. W. (2018). Hotelling Under Pressure, *Journal of Political Economy* **126**(3): 984–1026.

Andrews, M. J. (2021). Historical Patent Data: A Practitioner's Guide, *Journal of Economics & Management Strategy* **30**: 368 – 397.

Arora, A., Belenzon, S. and Sheer, L. (2021). Knowledge Spillovers and Corporate Investment in Scientific Research, *American Economic Review* **111**(3): 871–98.

Benson, C. L. and Magee, C. L. (2015). Quantitative Determination of Technological Improvement From Patent Data, *PloS One* **10**(4): e0121635.

Bonetti, P., Leuz, C. and Michelon, G. (2023). Internalizing Externalities: Disclosure Regulation for Hydraulic Fracturing, Drilling Activity and Water Quality, *Working Paper 30842*, National Bureau of Economic Research.

Cahoy, D. R., Gehman, J. and Lei, Z. (2012). Fracking Patents: The Emergence of Patents as Information-Containment Tools in Shale Drilling, *Mich. Telecomm. & Tech. L. Rev.* **19**: 279.

Clark, C. R. (2007). Advertising Restrictions and Competition in the Children's Breakfast Cereal Industry, *The Journal of Law and Economics* **50**(4): 757–780.

Clark, C. R., Doraszelski, U. and Draganska, M. (2009). The Effect of Advertising on Brand Awareness and Perceived Quality: An Empirical Investigation Using Panel Data, *Quantitative Marketing and Economics* **7**(2): 207–236.

Covert, T. R. (2015). Experiential and Social Learning in Firms: The Case of Hydraulic Fracturing in the Bakken Shale, *Working paper*, Harvard Business School.

Covert, T. R. and Sweeney, R. L. (2022). Secrecy Rules and Exploratory Investment: Theory and Evidence from the Shale Boom, *Working Paper 30548*, National Bureau of Economic Research.

Crompton, T. (2020). Digging Deep: A Rebounding Economy and Commodity Prices Will Renew Industry Demand, *Ibisworld industry report*, IBISWorld.

Cunningham, C. and Kapacinskaite, A. (2021). Keeping Innovation Confidential: The Role of Strengthened Appropriability in the Use of Trade Secrets, *Working paper*, London Business School.

Ellwanger, R. and Snudden, S. (2023). Futures Prices Are Useful Predictors of the Spot Price of Crude Oil, *The Energy Journal* **44**(4): 65–82.

Fell, H. and Kaffine, D. T. (2018). The Fall of Coal: Joint Impacts of Fuel Prices and Renewables on Generation and Emissions, *American Economic Journal: Economic Policy* **10**(2): 90–116.

Fetter, T. R., Steck, A. L., Timmins, C. and Wrenn, D. (2018). Learning by Viewing? Social Learning, Regulatory Disclosure, and Firm Productivity in Shale Gas, *Working Paper 25401*, National Bureau of Economic Research.

Fitzgerald, T. (2015). Experiential Gains with a New Technology: An Empirical Investigation of Hydraulic Fracturing, *Agricultural and Resource Economics Review* **44**(2): 83–105.

Fitzgerald, T. and Mason, C. F. (2021). Understanding Productivity Effects of Hydraulic Fracturing in Unconventional Natural Gas Deposits and Implications for Adoption in the Developing World, *Environment and Development Economics* **26**(3): 281–301.

Fukui, R., Greenfield, C., Pogue, K. and van der Zwaan, B. (2017). Experience Curve for Natural Gas Production by Hydraulic Fracturing, *Energy Policy* **105**: 263–268.

Gallegos, T. and Varela, B. (2015). Data Regarding Hydraulic Fracturing Distributions and Treatment Fluids, Additives, Proppants, and Water Volumes Applied to Wells Drilled in the United States From 1947 Through 2010, *U.S. Geological Survey Data Series 868* .

Ganglmair, B. and Reimers, I. (2019). Visibility of Technology and Cumulative Innovation: Evidence From Trade Secrets Laws, *Discussion Paper 19-035*, ZEW-Centre for European Economic Research.

Graham, S. and Hegde, D. (2015). Disclosing Patents' Secrets, *Science* **347**(6219): 236 – 237.

Hall, B. H., Jaffe, A. and Trajtenberg, M. (2005). Market Value and Patent Citations, *RAND Journal of Economics* **36**: 16–38.

Hall, B., Helmers, C., Rogers, M. and Sena, V. (2014). The Choice Between Formal and Informal Intellectual Property: A Review, *Journal of Economic Literature* **52**(2): 375–423.

Hegde, D., Herkenhoff, K. F. and Zhu, C. (2022). Patent Publication and Innovation, *Working Paper 29770*, National Bureau of Economic Research. **URL:** *http://www.nber.org/papers/w29770*

Higham, K., De Rassenfosse, G. and Jaffe, A. B. (2021). Patent Quality: Towards a Systematic Framework for Analysis and Measurement, *Research Policy* **50**(4): 104215.

Hodgson, C. (2021). Information Externalities, Free Riding, and Optimal Exploration in the UK Oil Industry, *Working paper*, Yale University.

Irwin, D. A. and Klenow, P. J. (1994). Learning-by-Doing Spillovers in the Semiconductor Industry, *Journal of Political Economy* **102**(6): 1200–1227.

Johnson, S. (2010). *Where Good Ideas Come From: The Natural History of Innovation*, Riverhhead books, New York.

Johnstone, N., Haščič, I. and Popp, D. (2010). Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts, *Environmental and Resource Economics* **45**(1): 133–155.

Kellogg, R. (2011). Learning by Drilling: Interfirm Learning and Relationship Persistence in the Texas Oilpatch, *The Quarterly Journal of Economics* **126**(4): 1961–2004.

Khan, B. Z. (2020). *Inventing Ideas: Patents, Prizes, and the Knowledge Economy*, Oxford University Press, USA.

Konschnik, K. and Dayalu, A. (2016). Hydraulic Fracturing Chemicals Reporting: Analysis of Available Data and Recommendations for Policymakers, *Energy Policy* **88**: 504–514.

MacGarvie, M. (2005). The Determinants of International Knowledge Diffusion as Measured by Patent Citations, *Economics Letters* **87**(1): 121–126.

Mason, C. F. (1989). Exploration Information and AEC Regulation of the Domestic Uranium Industry, *Journal of Economic Dynamics and Control* **13**(3): 421 – 448.

Mason, C. F., Muehlenbachs, L. A. and Olmstead, S. M. (2015). The Economics of Shale Gas Development, *Annual Review of Resource Economics* **7**(1): 269–289.

Mason, C. F. and Roberts, G. (2018). Price Elasticity of Supply and Productivity: An Analysis of Natural Gas Wells in Wyoming, *The Energy Journal* **39**(Special Issue 1).

Moser, P. (2013). Patents and Innovation: Evidence From Economic History, *Journal of Economic Perspectives* **27**(1): 23–44.

Nagypál, É. (2007). Learning by Doing vs. Learning About Match Quality: Can We Tell Them Apart?, *The Review of Economic Studies* **74**(2): 537–566.

Newell, R. G. and Prest, B. C. (2019). The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata, *The Energy Journal* **40**(3): 1–30.

Newell, R. G., Prest, B. C. and Vissing, A. B. (2019). Trophy Hunting Versus Manufacturing Energy: The Price Responsiveness of Shale Gas, *Journal of the Association of Environmental and Resource Economists* **6**(2): 391–431.

Platt, H. D. and Platt, M. A. (1989). Failure in the Oil Patch: An Examination of the Production and Oil Field Services Industries, *The Energy Journal* **10**(3): 35–49.

Png, I. P. L. (2017). Law and Innovation: Evidence from State Trade Secrets Laws, *The Review of Economics and Statistics* **99**(1): 167 – 179.

Popp, D. (2016). Economic Analysis of Scientific Publications and Implications for Energy Research and Development, *Nature Energy* **1**(4): 16020.

Popp, D. (2019). Environmental Policy and Innovation: A Decade of Research, *Working Paper 25361*, National Bureau of Economic Research.

Popp, D., Pless, J., Haščič, I. and Johnstone, N. (2020). *Innovation and Entrepreneurship in the Energy Sector*, University of Chicago Press, pp. 175–248. **URL:** *http://www.nber.org/chapters/c14375*

Rickman, D. S., Wang, H. and Winters, J. V. (2017). Is Shale Development Drilling Holes in the Human Capital Pipeline?, *Energy Economics* **62**: 283–290.

Rogers, H. (2011). Shale Gas—the Unfolding Story, *Oxford Review of Economic Policy* **27**(1): 117–143.

Steck, A. L. (2022). Industry Dynamics With Social Learning: Evidence From Hydraulic Fracturing, *Working Paper 7552*, Duke University.

Steffy, L. C. (2019). *George P. Mitchell: Fracking, Sustainability, and an Unorthodox Quest to Save the Planet*, Texas A&M University Press.

Sweeting, A., Jia, D., Hui, S. and Yao, X. (2022). Dynamic Price Competition, Learning-by-Doing and Strategic Buyers, *American Economic Review* **112**(4): 1311–1333.

Tang, T. (2018). Explaining Technological Change in the US Wind Industry: Energy Policies, Technological Learning, and Collaboration, *Energy Policy* **120**: 197 – 212.

Thompson, P. (2001). How Much Did the Liberty Shipbuilders Learn? New Evidence for an Old Case Study, *Journal of Political Economy* **109**(1): 103–137.

Wang, Z. and Krupnick, A. (2013). A Retrospective Review of Shale Gas Development in the United States: What Led to the Boom?, *Working Paper RFF-DP-13-12*, Resources for the Future.

Wiseman, H. J. (2011). Trade Secrets, Disclosure, and Dissent in a Fracturing Energy Revolution, *Columbia Law Review Sidebar* **111**(1): 1–13.

Wiseman, H. J. (2012). The private role in public fracturing disclosure and regulation, *Harv. Bus. L. Rev. Online* **3**: 49.

Figures

Figure 1: Patenting activity by participants in fracking service market:
Sellers (Service Companies) vs. Buyers (Operators)

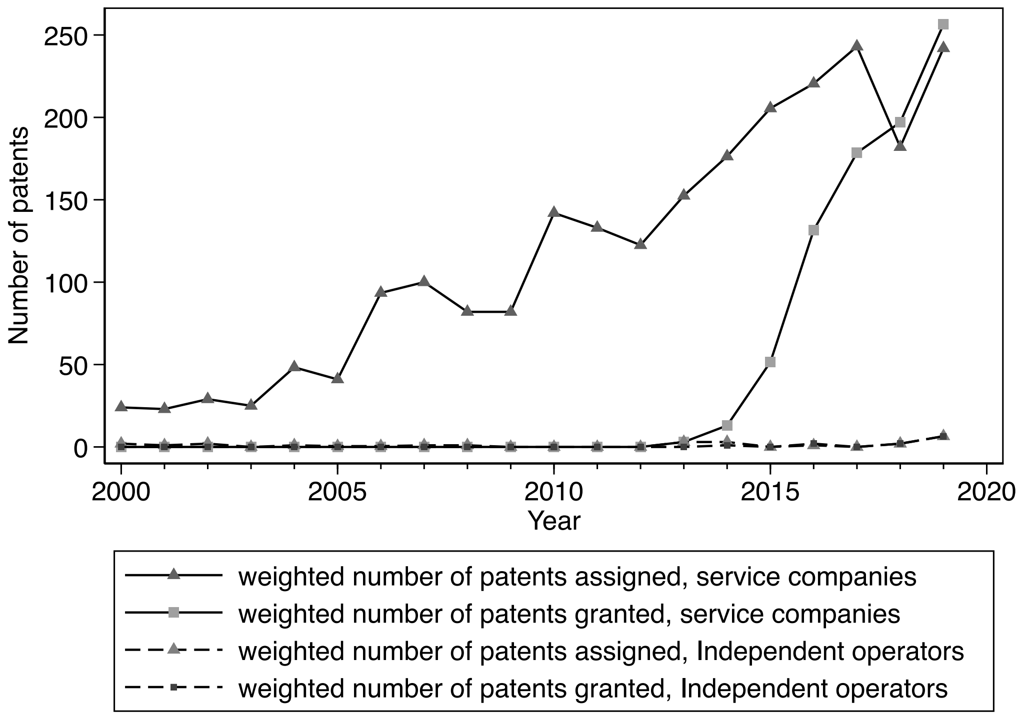


Figure 2: Publications by Firm Type, 2000–2019

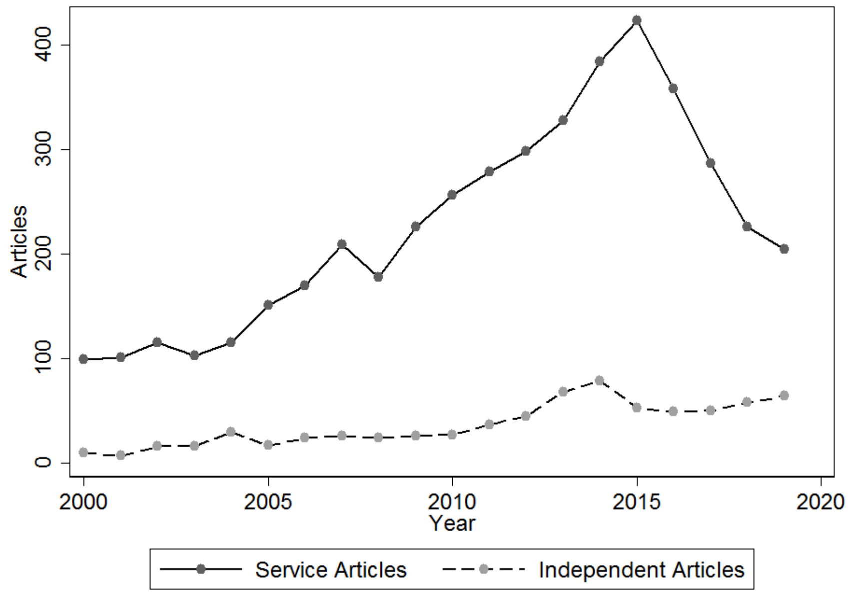


Figure 3: Hydraulic Fracturing Patent Applications and *JPT* Authorships, Big 3 vs. Other Service Companies 2000–2019

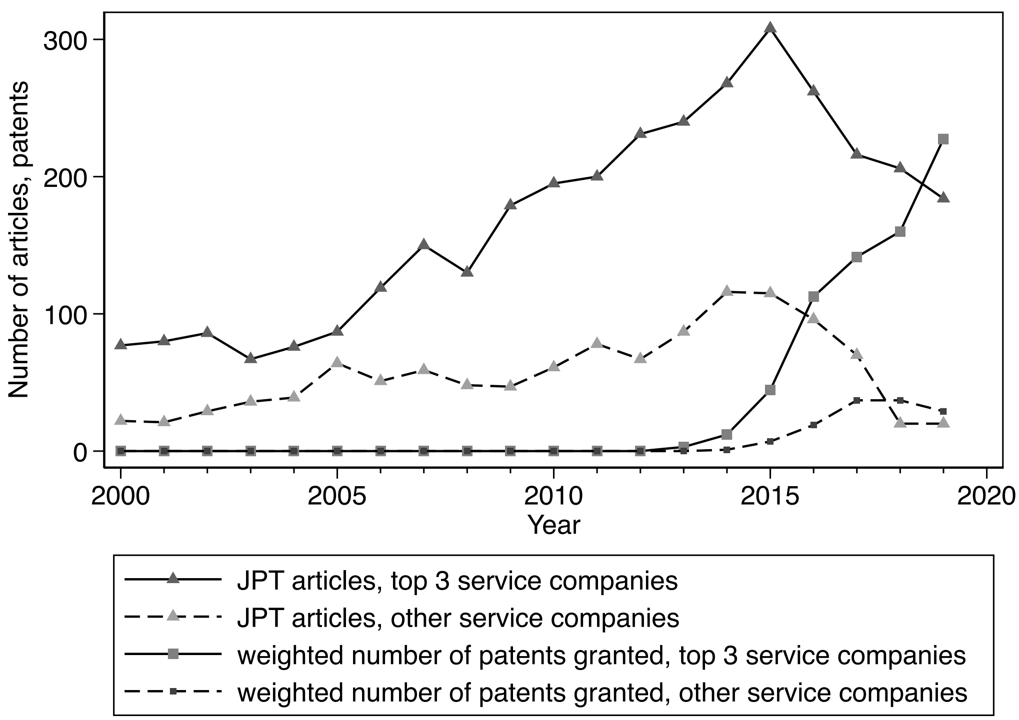
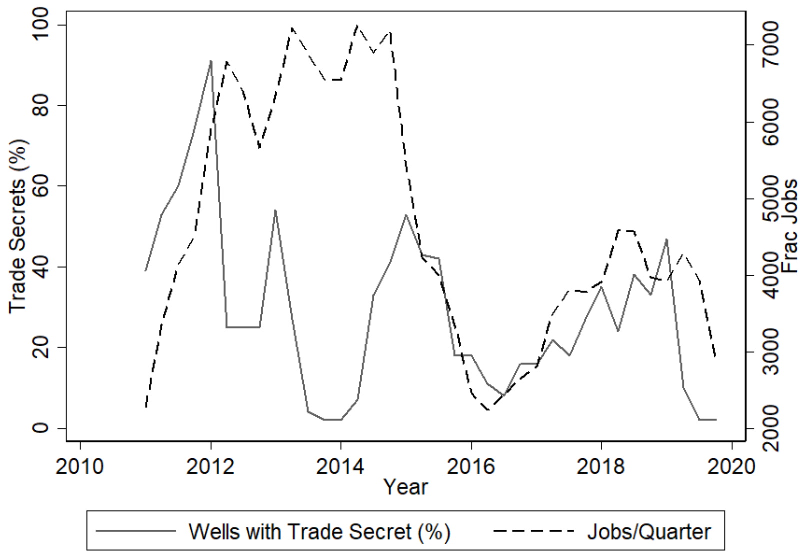


Figure 4: Trade Secrets and Frac Jobs, 2011–2019



Source: Primary Vision

Tables

Table 1: Buyer and Seller Concentration in Oil Service Market, 2011–2019

	National		State		Region	
Year	**Buyer**	**Seller**	**Buyer**	**Seller**	**Buyer**	**Seller**
2011	511	1352	1833	3028	1942	2763
2012	225	1218	1001	2414	1067	2110
2013	182	1074	905	2298	581	1993
2014	141	980	714	2141	763	1864
2015	152	1198	750	2440	922	2151
2016	136	1322	798	2429	839	2069
2017	107	1251	702	2520	706	2423
2018	105	1212	712	2646	705	2479
2019	125	1106	727	2453	765	2286

Notes: Authors' calculations based on data from Primary Vision. Table reports the Herfindahl-Hirschmann Index (HHI), which can be interpreted as a measure of market power; values are calculated separately for buyers and sellers. Values are reported for three levels of geographic granularity for each year: across the country as a whole (columns 2 and 3); averaged across producing states (columns 4 and 5); and averaged across each producing region (columns 6 and 7). Regions roughly conform to geological basins, which may span states (*e.g.*, Permian in TX and NM).

Table 2: Affiliation Classifications and Public Diffusion Shares

Category	Examples	Share (%) of authorships	Share (%) of patent applications
Contractor	FracGeo, MicroSeismic, Petro-Geotech	2.92	3.57
Independent Producer	Devon, Encana, Pioneer, Southwestern	2.67	0.08
Integrated Oil Company	Exxon, Chevron, BP	6.06	3.38
National Oil Company	Saudi Aramco, Pemex, Equinor	10.84	8.20
Academic/Institute	Universities, National Labs	33.38	8.76
Service Company	Halliburton, Schlumberger, Weatherford	20.12	52.13
Other	Battelle, Dow Chemical, Dupont, 3M	22.32	10.33
None Given		1.69	12.89
	Major Service Companies		
Baker Hughes		1.61	0.00
Halliburton		3.46	12.80
Schlumberger		7.47	31.07
Subtotal		12.54	43.87

Notes: Categories defined by authors. Share of authorships calculated across all *JPT* publications related to hydraulic fracturing over 2000-2019. Share of patents calculated across all granted patent applications related to hydraulic fracturing over 1976-2019.

Table 3: Patenting and Authorship by Affiliation, 2000–2019

	# papers (author-weighted)	# authorships (all authors)	# patent applicants	# patent assignments
Contractor	1,003	2,129	57	85
Independent	839	1,950	12	26
Major	1,682	4,425	54	436
NOC	2,750	7,906	131	145
Academic	8,721	24,357	140	189
Service Co.	4,948	14,680	833	2,376
Other	6,557	16,285	165	398
Unreported	820	1,234	4,626	2,382
Total	18,959	72,966	6,224	6,238

Notes: First two columns are based on sample of 18,959 papers published in JPT from 2000-2019. The first column identifies different types of affiliations of authors, as explained in table 2. The affiliation categories correspond to specialized contractors, independent operators, major operators, national oil companies, academic researchers, service companies, and a remainder category of all other affiliations. The Unreported categorization means that no affiliation was listed. The second column counts the total number of author-weighted papers. This assumes all coauthors contribute equally. One interpretation of the total is that the mean paper has 72,966/18,959 = 3.85 coauthors. The final column reports the total number of authorships by author affiliation. The patent data pertains to successful patent applications between 2000–2019. The third column counts each affiliated applicant, while the fourth column counts any patent assignment. The Other category includes businesses that are not primarily in the energy sector, while the Unreported categorization includes individuals and affiliations that are not identifiable.

Table 4: Productivity Impacts of Innovation: Sellers

	(1)	(2)	(3)	(4)
Patent Applications:				
recent SB	-0.032			
	(0.051)			
cumulative SB	0.611***			
	(0.099)			
recent HAL	-0.011			
	(0.039)			
cumulative HAL	0.608***			
	(0.100)			
recent Others	-1.759***			
	(0.604)			
cumulative Others	-0.602***			
	(0.101)			
Patents Assigned:				
recent SB		0.150***		
		(0.032)		
cumulative SB		0.002		
		(0.002)		
recent HAL		0.118***		
		(0.033)		
cumulative HAL		-0.001		
		(0.002)		
recent Others		-0.132		
		(0.986)		
cumulative Others		-0.334**		
		(0.154)		
Article Authorships:				
recent SB			-0.004	
			(0.048)	
cumulative SB			0.040***	
			(0.013)	
recent HAL			0.040	
			(0.055)	
cumulative HAL			0.043***	
			(0.013)	
recent Others			2.969***	
			(0.533)	
cumulative Others			-0.040***	
			(0.014)	
Weighted JPT Citations:				
recent SB				-0.008
				(0.024)
cumulative SB				0.100***
				(0.017)
recent HAL				-0.015
				(0.055)
cumulative HAL				0.104***
				(0.017)
recent Others				1.428***
				(0.186)
cumulative Others				-0.100***
				(0.017)
No. of secret wells	0.004	0.005	0.005	0.004
	(0.003)	(0.004)	(0.004)	(0.004)
Quarterly WTI spot price	2.786***	2.464***	2.580***	2.523***
	(0.725)	(0.779)	(0.767)	(0.757)

Notes: Dependent variable is log of average 12 month BOE (productivity) for all wells completed by a seller in a year. Independent variables are lagged one quarter. All regressions include year and firm fixed effects. SB: Schlumberger; HAL: Halliburton. Newey-West standard errors in parentheses. Number of observations: 911, regressions 1 and 2; 706, regressions 3 and 4. Asterisks indicate statistical significance of coefficient estimate: * $p<0.1$, ** $p<0.05$, *** $p<0.01$.

Table 5: Productivity Impacts of Innovation: Buyers

	(1)	(2)	(3)	(4)
Recent patent applications	0.719**			
	(0.351)			
Cumulative patent applications	-0.211**			
	(0.085)			
Recent patents assigned		0.446***		
		(0.141)		
Cumulative patents assigned		-0.098***		
		(0.027)		
Recent article authorships			0.158	
			(0.143)	
Cumulative article authorships			-0.017**	
			(0.007)	
Recent article weighted citations				0.003
				(0.020)
Cumulative article weighted citations				-0.001
				(0.005)
No. of secret wells	0.000	0.001	0.002	0.001
	(0.006)	(0.006)	(0.007)	(0.007)
Quarterly WTI spot price	0.409	0.400	0.159	0.173
	(0.469)	(0.469)	(0.673)	(0.674)

Notes: Dependent variable is log of average 12 month BOE (productivity) for all wells completed by a seller in a year. Independent variables are lagged one quarter. All regressions include year and firm fixed effects. Newey-West standard errors in parentheses. Number of observations: 2,569, regressions 1 and 2; 1,707, regressions 3 and 4. Asterisks indicate statistical significance of coefficient estimate: * $p<0.1$, ** $p<0.05$, *** $p<0.01$.

Table 6: Effect of Production and Secret Wells on Market Share

	Buyers	**Sellers**
Log 12 Month BOE	0.087***	0.617***
	(0.008)	(0.140)
No. of secret wells	0.058***	0.073**
	(0.008)	(0.024)
No. of Observations	2,492	336

Notes: Dependent variable is annual market share, calculated separately for oil service sellers and buyers. Year fixed effects included but not reported. Data source is Enverus and Primary Vision. Newey-West standard errors in parentheses. Asterisks indicate statistical significance of coefficient estimate: * p<0.1, ** p<0.05, *** p<0.01.

Table 7: Predicting Market Share Using Innovation as IV for Productivity

	Buyers	**Sellers**
Log 12 Month BOE	0.337	11.449***
	(0.432)	(2.714)
No. of secret wells	0.041***	0.131*
	(0.012)	(0.059)
No. of Observations	471	206
First Stage F statistic	57.563	9.508
Hansen J statistic	2.647	2.807

Notes: Dependent variable is national annual market share, calculated separately for operators and service companies. Instruments used for Log 12 Month BOE include vector of innovation measures discussed above (Patent Applications, Patents Assigned, JPT Article Authorships, Weighted JPT citations) and WTI spot price. Year fixed effects included but not reported. Driscoll-Kraay standard errors in parentheses. Hansen J is statistically insignificant, rejecting hypothesis of overidentification. Asterisks indicate statistical significance of coefficient estimate: * $p<0.1$, ** $p<0.05$, *** $p<0.01$.

A Data Provenance

A.1 Primary Vision

Primary Vision is a Los Angeles-based data provider. The Primary Vision Frac Spread Count is a high-profile product that is widely used in the industry as an analogue to drilling rig counts. Primary Vision also provides detailed frac consumables datasets. Our analysis is based on a dataset that identifies individual frac jobs, including detailed information about the well, operator, and servicer providing pressure pumping for each well.

The base data for our analysis is the December 17, 2020 data distribution by Primary Vision. That version includes a total of 166,547 frac jobs in the period 2011–2019. These jobs were performed on a total of 159,158 distinct wells (using a 14-digit API number). A total of 75 different service companies are recorded as the pressure pumper of record for those jobs, although in no year are that many firms active. Table 8 reports the number of firms performing at least one frac job in the United States in each year. The data include at least one frac job for a total of 1501 operators. There are a total of 4615 different pairings of pumpers and operators.

Table 8: Entry in Pressure Pumping Sector, 2011–2019

Year	**Active Pressure Pumpers**
2011	37
2012	53
2013	59
2014	57
2015	50
2016	51
2017	48
2018	42
2019	43

Source: Primary Vision

A.2 Enverus

Enverus (formerly DrillingInfo) is an Austin-based data and analytics provider. We used flat files provided through special arrangement between Enverus and academic researchers. These data include detailed well production histories for all wells in the United States, which we used to calculate well-specific productivity measures. These measures use allocated production for Texas, where production is reported at the lease rather than the well level. We treat those allocated production measures as though they were well-level reports.

By establishing production at the well-level, we are able to match the first 12 months of production after a frac job on a particular well by matching Primary Vision and Enverus data. Table 9 shows the aggregate improvement in production over time as the application of the technology improved. Table 10 illustrates how large the differences in productivity are across operators and service companies. The most active firms in each category are included in the table. The table reports the number of observed frac jobs, and then lagged average production, expressed in logs of barrel of oil equivalents (BOE). Mean productivity differences are not explained by experience, though the correlations between total experience and maximum production are stronger (0.37 for service companies, 0.52 for operators).

Table 9: Well Productivity, 2011–2019

	Log 12 Month BOE		
Year Completed	**Mean**	**SD**	**Range**
2011	10.79058	1.345126	14.42055
2012	10.49588	1.449923	13.07488
2013	10.59073	1.483198	12.75701
2014	10.79627	1.422998	13.68916
2015	11.16357	1.360479	12.93405
2016	11.5023	1.360147	13.05957
2017	11.63366	1.334205	12.53319
2018	11.7967	1.266269	14.42402
2019	11.84371	1.268892	13.56388
Cumul.	11.06111	1.383235	13.35971

Notes: This table reports first 12 month BOE (in logs) from Enverus by year of completion/frac job for a total of 135,323 wells with matched frac jobs from Primary Vision.

Table 10: Comparison of Well Productivity Between Most Active Service Companies and Operators

Service Company				Operator			
	Job	Log 12 Month BOE			**Job**	Log 12 Month BOE	
	Count	**Mean**	**Max**		**Count**	**Mean**	**Max**
US Well	996	12.572	14.086	Antero	916	12.822	14.086
Keane	1,770	12.496	14.425	Cabot	837	12.751	14.358
BJ Services	1,531	12.170	14.662	EQT	1,080	12.480	14.302
Liberty	2,918	11.744	13.570	Cimarex	903	12.081	13.917
FTSI	5,202	11.721	14.421	Continental	2,352	11.773	14.222
Perf Tech	1,343	11.547	13.819	Marathon	2,430	11.769	14.425
Pumpco	1,331	11.442	13.614	EOG	4,708	11.703	14.143
Universal	3,081	11.413	14.201	Oasis	853	11.643	13.059
SEECO	1,929	11.377	12.418	Hess	1,590	11.621	13.161
Halliburton	33,994	11.292	14.382	Chesapeake	6,026	11.603	14.662
Sanjel	1,595	11.254	13.193	ConocoPhillips	2,316	11.492	14.376
Schlumberger	12,952	11.242	15.519	PDC Energy	1,001	11.434	13.280
Trican	2,113	11.128	14.046	EP	1,144	11.336	13.890
Calfrac	4,345	10.987	14.203	EnCana	2,126	11.335	13.925
C&J	2,588	10.978	14.479	Noble	2,225	11.051	13.538
Pioneer	2,240	10.774	13.330	Devon	3,726	11.046	14.040
Weatherford	4,589	10.629	14.016	Anadarko	6,194	11.025	13.614
ProPetro	3,167	10.595	13.767	Concho	1,543	10.755	13.972
Nabors	2,400	10.567	14.139	Newfield	2,197	10.743	13.624
Superior	1,197	10.469	13.943	Chevron	2,247	10.531	13.689
Baker Hughes	11,576	10.187	14.143	Apache	3,336	10.352	13.634
				Oxy	3,174	10.338	14.382
				Energen	1,291	9.711	13.316
All Other (n=56)	22,458	10.615	14.239	All Other (n=1,174)	47,560	10.795	15.519
Total	125,315	11.045	15.519	Total	125,315	11.045	15.519

Notes: Authors' calculations from data provided by Primary Vision and Enverus.

A.3 *JPT* Citations

The *Journal of Petroleum Technology* (*JPT*) is the flagship publication of the Society of Petroleum Engineers (SPE), which is the leading organization dedicated to petroleum engineering issues. Among other functions for the Society, the *Journal* presents authoritative briefs and features on E&P technology advancements and industry issues. This makes it a popular forum for industry practitioners. Ready access at http://onepetro.org/JPT also makes this an attractive target.

There are many alternative publication outlets. For example, the SPE sponsors four other peer-reviewed outlets. And there are non-SPE alternatives such as the *Journal of Petroleum Science and Engineering*. However, none of these share the wide audience and relatively easy accessibility of *JPT*.

The authors and affiliations of the individual articles were classified according to the categories described in table 3 of the manuscript. Not every author reports an affiliation, and some reported affiliations are difficult to identify from reported information.

A.4 Patents

Using U.S. Patent and Trademark Office public records, we searched for all granted patents including the keywords "hydraulic fracturing." This public dataset extends back to 1976. We then processed the results and applied the same classifications of individual applicants and assignees as were used for the publications.

Many individuals apply for patents and it is not possible to link such individuals to a particular affiliation from the available information. Such individuals are treated as unaffiliated. Such individual unaffiliated patent filers are presumably rewarded when their patents are assigned to a larger entity.

B Appendix Figures

Figure B.1: Distribution of Jaccard Index Describing Similarity of Hydraulic Fracturing Additives in PA, from Fetter et al. (2018)

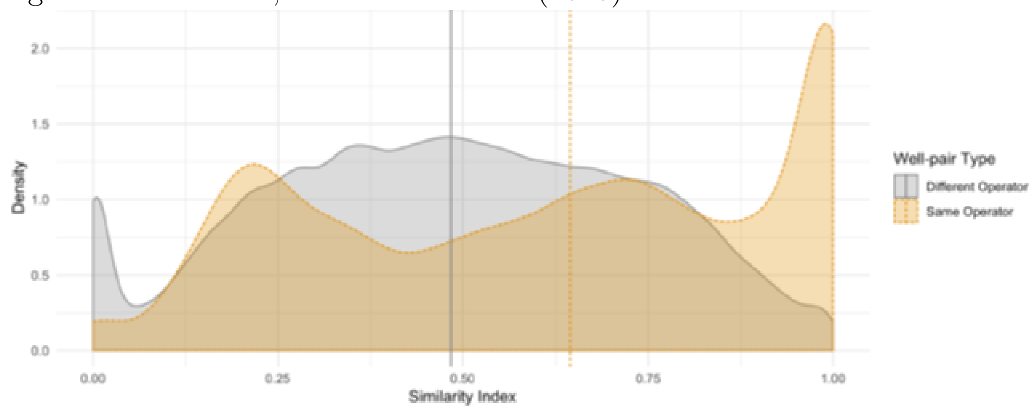


Figure B.2: Distribution of Jaccard Index Describing Similarity of Hydraulic Fracturing Additives in Sublette County, WY