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Hydraulic Fracturing Technology and Its Economic and Environmental Impacts

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Abstract

Given the urgent need for energy resources, many major energy-producing and consuming countries are seeking new sources to contribute to the sustainability of global energy supplies. The United States possesses vast reserves of unconventional oil and gas resources, such as shale formations and dense rocks. This research aims to highlight hydraulic fracturing technology used in developing unconventional hydrocarbon energy sources, the use of which requires favorable economic conditions, namely high conventional oil prices. The research problem stems from OPEC's disregard for the role of high oil prices, which have created opportunities for developing unconventional oil extraction technologies. The most significant finding of the research is that high oil prices have enabled the development of unconventional hydrocarbons and reduced OPEC's share of global oil production. The research recommends limiting price increases to levels that allow for the development of unconventional hydrocarbon resources.

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1-Introduction

Hydraulic fracturing (commonly called "fracking," but now often referred to as HF) is a technique for extracting natural gas and other hydrocarbons from shale, Although hydraulic fracturing is often presented as a relatively new technology, it is best understood as a combination and development of two well-established techniques: horizontal drilling of underground wells and the use of pressurized fluids to enhance oil and gas well production and capture gas molecules from the fluids. Horizontal drilling, the process of drilling underground wells horizontally, was first implemented in the United States in the 1920s. Hydraulic fracturing, the injection of pressurized fluids to enhance oil and gas recovery, dates back to the late 1940s in the United States (Green, 2024,) (1)

While fracking has increased fossil fuel extraction, it is a controversial technique in the U.S. and around the world due to its effects on the environment and human health (Boyle, 2021) (2). While increased oil and natural gas production resulting from hydraulic fracturing benefits workers and the U.S. economy, the health risks it poses harm hundreds of thousands of U.S. residents, especially Colorado residents. Recent studies have shown that people living within 3,000 feet of a fracking well are more susceptible to adverse skin and upper respiratory symptoms (Rabinowitz et al., 2015) (3).

The Importance of the Research: The significance of this research lies in the role of hydraulic fracturing technology in developing unconventional hydrocarbon energy sources.

The Objective of the Research: This research aims to review the most significant developments in the global oil industry following the adoption of hydraulic fracturing for the extraction of unconventional oil and shale gas, and to assess the environmental impacts of this technology. The research also seeks to highlight the major gains achieved by this technology, namely the increase in the volume of proven unconventional hydrocarbon discoveries and reserves. The Research Problem: The research problem centers on demonstrating that the disregard shown by oil-producing countries, including those affected by high oil prices in recent years, has created opportunities for developing extraction technologies for unconventional hydrocarbon sources. This will have implications for the future role that countries with abundant reserves of these two resources may play in the energy market.

The Research Hypothesis: This research hypothesizes that hydraulic fracturing technology, developed in consuming countries and widely used to extract unconventional oil and shale gas, has contributed to reductions in these countries' energy deficits.

Research Methodology:

The research employed a descriptive-analytical approach based on available data and statistics, as well as international references and sources.

The history of oil and hydraulic fracturing technic

The modern history of oil begins in 1853 with the discovery of the oil distillation process. Ignacy Lukasiewicz, a Polish scientist, distilled oil to obtain kerosene. However, the true oil industry didn't begin until 1859 when Edwin Drake successfully drilled the first oil well in Titusville, Pennsylvania. Oil exploration then moved westward toward Ohio and Indiana. Between 1862 and 1869, wells were drilled in Pulaski and Vigo counties, where oil and gas were discovered, but the fields remained undeveloped. The growth of the oil industry was relatively slow in the 19th century, largely driven by the limited demand for kerosene and oil lamps. At the beginning of the 20th century, the oil industry in the United States became a national priority, particularly with the advent of internal combustion engines, which significantly increased industrial demand for oil. Early discoveries in Pennsylvania and Ontario led to oil shortages in Texas, Oklahoma, and California. Furthermore, by 1910, large oil fields had been discovered in Canada, the East Indies, Iran, Venezuela, and Mexico (Stec, 2022) (4)

However, oil exploration methods remain complex and require substantial investment. These methods have reached a high level of technological development in seismic, magnetic, and electrical surveys—on land, at sea, and in the air—with advances enabled by specialized computers. The movement of geological layers, and the resulting faults, trenches, folds, and interactions, lead to significant variations in rock properties, even in adjacent areas. The presence of geological structures does not necessarily indicate the presence of oil. Furthermore, all currently available exploration methods cannot definitively identify oil deposits within the pores of primary or secondary sedimentary rocks in a specific area. These deposits are often found alongside other materials, primarily groundwater and various impurities. Therefore, oil does not occupy 100% of the available porosity in oil traps, whether structural or sedimentary.

These methods have advanced considerably in their technological development. On the other hand, the amount of oil present in a rock layer often represents only a small part of the total volume of the oil-bearing layer. The nature of oil saturation in the pores of sedimentary layers allows for a high ability to extract a certain amount of oil, while another amount is attached to the surfaces of the grains that make up the rocks with an attachment that may be chemical and cannot be extracted except by carrying out high-cost operations to change the properties of this attachment. Hence, it is necessary to drill exploration wells to evaluate the oil field with respect to the feasibility of extraction, the size of the oil reservoir, the potential for development of the discovery, and the collection of additional data on the underground reservoir (Al-Abadey) (5).

One of the most recent methods used in oil extraction is multi-stage hydraulic fracturing. Hydraulic fracturing is a treatment applied to reservoir rocks to improve the flow of trapped oil or natural gas from its initial location to the wellbore. This process involves creating fractures in the rock formation and injecting a mixture of water, sand, and chemicals to maintain their open state. Fracturing is achieved by injecting water and fluids designed for the specific location under high pressure in an engineered,

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monitored, and controlled process. Essentially, it is a process in which pore pressure builds up; by injecting fluids into the wellbore, the pressure becomes high enough to fracture the rocks that trap hydrocarbons. This technique is widely used in the oil industry to enhance wellbore permeability near the reservoir. Thus, hydraulic fracturing has become essential to shale gas production, as producers seek to maximize shale fracture at minimal cost (Wangen, 2011) (6). Hydraulic fracturing technology has been developed over more than half a century since its successful testing in 1947. As an effective technical measure to increase production, it has been widely used to exploit low-permeability oil and gas basins. However, in the context of underground drilling, research on hydraulic fracturing has been limited to the exploitation of associated oil and gas reservoirs and geothermal energy sources. The former Soviet Union began testing hydraulic fracturing in an underground coal mine in the 1960s (XU et al., 2011) (7).

The U.S. Department of Energy concluded as early as 1978(8) that developing a domestic oil shale industry was technically feasible (using hydraulic fracturing) and that it was ready for the next steps toward the aggressive marketing of crude oil. However, by 1984, declining tensions in the Middle East, the availability of new oil supplies from non-OPEC sources, including North Sea production, and falling global oil demand caused oil prices to fall from $31 per barrel to $10 per barrel. Thus, many projects under construction or undergoing practical testing in the United States became economically infeasible and were subsequently terminated (Department of Energy, 2004,(8).

Hydraulic fracturing using coiled tubing has become a cost-effective well stimulation technique, creating fractures in rock formations across various zones. Coiled tubing fracturing has made significant progress since its first application in 1993. In hydraulic fracturing, fracturing fluids are injected at sufficiently high rates to exceed the rock's tensile strength, thereby fracturing the rock and maintaining its permeability. Sufficient fluid is also injected to ensure the required fracture dimensions. The fracturing mud injected into the fractures contains proppant (solid particles), which keeps the created channels open after treatment and maintains the closing pressures of these channels. In typical rock fracturing, a total of 50-100 tons of propane is pumped during stimulation between 3 and 8 stages. The mud is pumped through a 6 cm diameter coiled pipe at a rate of 1.43 to 1.91 cubic meters per minute (Shah and Jain, 2008, 279). By 2002, this practice had been used extensively, exceeding one million times, reaching a usage rate of 95% in wells drilled in the United States, representing 43% of US oil production and 67% of US natural gas production (NPC, 2011) (9).

How Hydraulic Fracturing Works and the Oil Prices at Which It Can Be Used:

The use of unconventional oil and gas production technologies is increasing due to the ever-growing demand for energy. Therefore, exploiting unconventional reservoirs through hydraulic fracturing (fracking) is an inevitable option in this industry. Hydraulic fracturing involves injecting large volumes of high-pressure fracturing fluid into tight shale formations to fracture the rock and create flow paths for the extraction of trapped oil and gas (Makki et al., 2025) (10).

It is worth noting that hydraulic fracturing has been a technological breakthrough, significantly increasing production rates in late-stage wells. This is because hydraulic fracturing increases oil recovery efficiency, a technological metric for field development that measures the amount of fluid that rises to the surface relative to the total reservoir volume. With increased oil recovery efficiency, more oil can be extracted from a single well, eliminating the need to drill new wells for further reservoir development. Furthermore, this technology enabled the development of unconventional oil reservoirs, leading to the so-called shale oil revolution in the United States and other countries. Therefore, in older fields in Russia, such as Ust-Balikskoye and Mamontova, the use of hydraulic fracturing has enabled increased production, prevented planned declines, and revitalized older reserves in various ways(Zhironkin and Cehlar, 2021) (11).

The workings of this technique can be summarized in the following steps:

Step 1: A vertical well is drilled thousands of feet into the earth. As drilling continues, a protective steel pipe (casing) is inserted, and the well is then cemented to prevent water and subsurface materials from reaching it.

Step 2: The drilling then transitions from vertical to inclined, and finally to horizontal drilling to reach the oil and gas reservoirs within the shale formations. After inserting another steel pipe, the horizontal well is cemented again for the same reason.

Step 3: Perforated pipes are then inserted into the target areas containing oil or gas. The rock is then perforated using a rock drilling machine with explosives. After this stage, hydraulic fracturing begins. The fracturing process involves injecting a mixture (using trucks on the surface) of fluids (water), sand (propant), and other chemicals at extremely high pressure into perforated pipes still below the surface. This creates small fractures in the shale formations, allowing the oil and gas to escape and flow upwards into the well for later extraction.

The sand prevents fractures from sealing when injection stops (other types of sand, such as ceramic, may also be used; many experts believe they are more effective than propant). The chemicals facilitate adaptation of the

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injection material to specific geological conditions, thereby protecting the well and improving its performance. Once the fractures are created, the injection of the fluids and fracturing fluids ceases, and the fluids begin to flow back to the surface. Horizontal fracturing operations occur in several stages, not just a single stage. They sometimes occur every 300 feet along the horizontal arm of the wellhead. Each stage involves the repeated injection of sand, water, and chemicals into specific areas of the well. Multiple fracturing stages enable continuous increases in production. Despite its complexities, most shale oil and tight US oil are considered profitable today at a price between $50 and $65 per barrel for West Texas Intermediate (WTI) (Maugeri, 2012) (12). A British study conducted in 1977 indicated that, given the prevailing technical conditions at the time, oil shale could be profitablely produced in the western United States when the price of oil was $18 per barrel (in 1975 dollars) (Ericsson and Morgan, 1978(13).

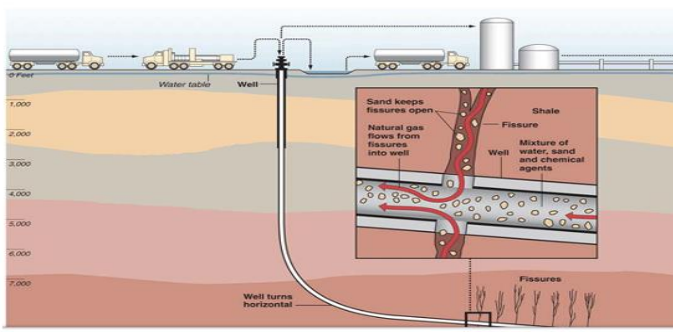

Figure (1) How hydraulic fracturing works.

Source: Maugeri, Leonardo (2012) Oil: The Next Revolution, Harvard Universi Discussion Paper 10, P .43

When fracturing the shale layer, the rock is perforated using a remotely controlled explosive wireline drilling tractor. The multi-fracture perforation process for horizontal completion was adopted early in the development of the Barnett shale. It is a common process and is referred to as the "perf & plug" method. This method is usually used with casing and cementing of the well. An initial set of holes can be created using coiled pipes or using a wireline drilling tractor carrying an explosive perforating weapon, as shown in Figure (2). Even when efficient operations could be achieved, production logging showed that, at best, only 50% of the intended fracturing targets would actually produce at incentivized fracturing rates. In many cases, even with horizontal completion through casing, cementing the wellbore, and perforation, 80% of the production contributed by this technique came from only 20% of the perforated locations along the shale formations (Soliman et al., 2012) (14).

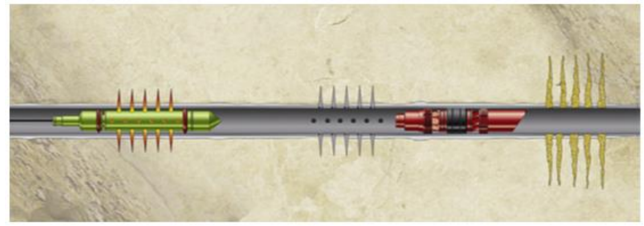

Figure (2) the mechanism of operation of the oil shale perforation technique using a wire tractor

Source: Soliman et al, (2012) Fracturing unconventional formations to enhance productivity", Journal of Natural Gas Science and Engineering, vol. 8, P. 53

Hydraulic fracturing technic effects on environment

The advanced technologies such as horizontal drilling and hydraulic fracturing have, for the first time, achieved profitable extraction of natural gas from deep shale formations. Both the economic benefits and environmental risks of unconventional gas extraction are concentrated in areas near deep shale gas reservoirs. While drilling and extraction generate economic returns and provide employment opportunities in these areas, drilling operations require large quantities of water, and the recovery of this water (fracking water used in the drilling process) requires careful handling that can threaten the natural environment (Kinnaman, 2011) (15).

Several U.S. states have imposed a moratorium on hydraulic fracturing (fracking) due to concerns about drinking water contamination. New York State, in particular, appears poised to take measures to restrict fracking for the same reason, but it is unclear whether the current moratorium on horizontal drilling will be renewed. Even if anti-fracking groups are successful in some areas, this is unlikely to happen in others (Rahm, 2011) (16).

The use of hydraulic fracturing (fracking) in shale gas and oil production can cause severe environmental problems in the production area, potentially affecting the health and lives of field workers and nearby residents. This impact extends beyond groundwater to include seismic activity. Furthermore, according to research by American scientists, shale gas production using hydraulic fracturing contributed to the earthquakes in Ohio in 2013(Zhironkin and Cehlar, 2021(11).

By comparing the negative environmental impacts of energy obtained from both conventional and unconventional sources (specifically, hydraulic fracturing), a 2013 US study on shale gas extracted via hydraulic fracturing versus coal found that switching from coal to shale gas can benefit public health, worker safety, local environmental protection, water consumption, and ultimately, the land surface. The study also found that shale gas likely has a smaller greenhouse gas footprint than coal,

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but its extraction can still affect water quality (Jenner and Lamadrid, 2013) (17).

How to reduce the economic importance of unconventional hydrocarbons

Prior to the dramatic rise in oil prices in 2008, most economic studies by economists specializing in oil and energy economics did not consider the significant role of unconventional hydrocarbons, such as those extracted from shale rock, in changing the rules of the game in the global energy market. Many of these studies focused on the role of non-OPEC countries and their impact on OPEC's crude oil production and prices. For example, a 2004 study by Robert Kaufmann et al., which analyzed several OPEC countries, emphasized the importance of increased production from some non-OPEC countries (most notably Russia), whose output posed a potential threat to OPEC's ability to influence oil markets (Kaufmann et al 2014) (13),

Table (1) Development of conventional and unconventional oil production in the US

	World Oil Price USD Per barrel	US Oil Production Million barrels daily	US Oil Reserve Billion barrel	US Gas Reserve Trillion cubic meters	OPEC /Global Oil Production (%)
2000	28.38	5.822	21.765	5.020	43.24
2001	24.39	5.801	22.045	5.222	42.23
2002	24.93	5.744	22.446	5.290	39.39
2003	28.88	5.681	22.677	5.293	41.93
2004	37.76	5.419	21.891	5.454	44.07
2005	52.63	5.178	21.371	5.787	45.09
2006	64.22	5.102	21.757	5.925	44.06
2007	70.84	5.064	20.972	6.730	43.66
2008	97.20	4.951	21.317	7.468	44.69
2009	61.58	5.353	19.121	7.468	41.94
2010	78.91	5.479	20.682	7.075	41.85
2011	104.07	5.652	23.267	8.627	42.77
2012	104.95	6.505	26.544	9.461	44.55
2013	104.04	7.545	33.000	11.011	43.35
2014	96.41	8.759	36.385	11.012	41.75
2015	50.77	9.431	32.318	8.709	42.09
2016	42.70	9.352	32.773	9.119	43.86
2017	52.67	10.962	39.160	12.408	43.14
2018	68.89	10.992	43.824	13.447	41.91
2019	61.65	12.311	44.191	14.254	37.43
2020	41.17	11.318	35.835	13.171	35.46
2021	69.31	11.268	41.610	16.674	36.39
2022	97.43	11.911	45.271	16.674	38.12
2023	81.20	12.927	47.730	17.410	36.59
2024	78.81	13.400	48.823	17.800	36.17

Source: OPEC Annual statistical bulletin 2005-2025

Since the International Energy Agency defines conventional oil as "a mixture of hydrocarbons that are in the liquid state under normal surface conditions" in its World Economic Outlook 2011 report, it is important to understand the difference between conventional and unconventional oil. The main difference lies in the cost and ease of production. Conventional oil is cheaper and easier to produce than unconventional oil. However, given technological advancements, unconventional oil could become conventional in the future (Biresselioglu, 2017)(18).

Table (1) illustrates after the rise in the average global price of oil, especially after 2008, the volume of US daily oil production (conventional and unconventional oil) increased and reached its peak in 2024. The same applies to the volume of US reserves of crude oil and natural gas. All these things combined reduced OPEC's share of global oil production.

OPEC can reduce the economic importance of unconventional hydrocarbons by strategically increasing its own production to lower global prices, which makes higher-cost unconventional oil less competitive. It can also leverage its market power to influence global oil prices and supply, potentially discouraging investment in new unconventional projects. Additionally, OPEC countries can invest in alternative energy sources and economic diversification to reduce their own reliance on oil.

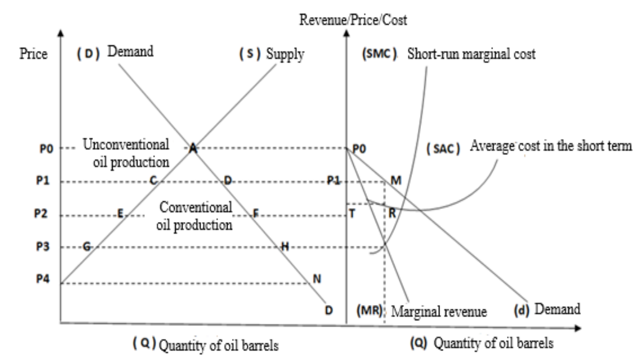

Figure (3) price leadership model based on the larger production volume of conventional oil
Source: Al-Hiti, Ahmed Hussein (2000),Oil Economics, Dar Al-Kutub for Printing and Publishing, Mosul,P111

Figure (3) illustrates the price leadership model based on the larger production volume of conventional oil. If the leading producer sets the price at level P0, it allows secondary producers of unconventional oil (or hydrocarbons) to meet the entire market demand, i.e., the distance P0A. However, if the leading producer lowers the price to level P1, this will reduce the share of secondary producers of unconventional oil and increase the leading producer's share of conventional oil, resulting in the following: the share of secondary producers equals the distance P1C, and the share of the leading producer equals the distance CD. It is observed from this figure that the leading producer's share will increase as it reduces the price per barrel of oil in the market, until it becomes the supplier of all market demand at the very low price P4, a distance P4N. At this low-price level, the share of secondary producers of unconventional oil disappears. This was the case prior to 2008, as low crude oil prices prevented secondary producers of unconventional oil from developing their production, despite the availability of the necessary technology. However, the economic conditions, represented by Low prices that discouraged the development of production, had the final say in this matter. Thus, the leading producer, by controlling price movements, can allow or prevent secondary producers of unconventional energy sources from entering the market, thereby expanding or reducing the share of conventional oil relative to its unconventional counterpart (Al-Hiti, 2000, (19).

Conclusions and Recommendations:

Unconventional oil and natural gas are two depleting hydrocarbon resources that can be extracted from deep shale formations using hydraulic fracturing, provided the necessary technical and economic conditions are met. The rise in global oil prices has accelerated the development of unconventional oil and gas resources, following the availability of the necessary economic and technical conditions for extracting them from shale rock, which is abundant in the United States. Hydraulic fracturing, the technique used to extract oil and gas, is widely regarded as environmentally polluting. Its use has been banned in some countries due to its harmful effects on human health, stemming from the transfer of chemicals into groundwater, which humans use directly through consumption and indirectly for irrigating crops and watering livestock.

Oil-producing countries can control the number of unconventional hydrocarbons entering the market by manipulating pricing mechanisms. This can reduce the extraction of this type of hydrocarbon, whose high extraction costs are a burden that producers must bear to compete with less expensive conventional hydrocarbons.

The United States possesses enormous shale reserves containing hydrocarbons, enabling it to produce unconventional oil and gas. This could potentially make it an oil-exporting country in the future. Therefore, it is essential to prevent global oil prices from rising to a level that would allow hydraulic fracturing (fracking) technology to continue operating.

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تقنية التكسير الهيدروليكي وآثارها الاقتصادية والبيئية

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الخلاصة:
نظراً للحاجة المُلِحّة لمصادر الطاقة، فإن العديد من البلدان الرئيسة المُنتجة والمستهلكة للطاقة تسعى إلى الحصول على مصادر جديدة تُساهم في استدامة إمدادات الطاقة العالمية، وفي الولايات المتحدة الامريكية توجد احتياطيات هائلة من موارد النفط والغاز غير التقليدية، من مثل تكوينات الصخر الزيتي والصخور الكثيفة وغيرها. يهدف البحث إلى تسليط الضوء على تقنية التكسير الهيدروليكي المُستخدمة في تطوير مصادر الطاقة الهيدروكربونية غير التقليدية، التي يتطلب استخدامها توافر ظروف اقتصادية متمثلة في ارتفاع أسعار النفط التقليدي. تأتي مشكلة البحث من تجاهل أوبك لدور أسعار النفط المرتفعة الذي أتاح فرصاً لتطوير تقنيات استخراج مصادر النفط غير التقليدية. وتتمثل أهم نتائج البحث في أن ارتفاع أسعار النفط قد سمح بتطوير الهيدروكربونات غير التقليدية وخفض حصة أوبك في إنتاج النفط العالمي. وأوصى البحث بالحد من زيادات الأسعار إلى مستويات تسمح بتطوير مصادر الهيدروكربونات غير التقليدية.