NATURAL GAS AS A BRIDGE FUEL TOWARD RENEWABLES

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"A new scientific truth does not triumph by convincing its opponents and making them see the light,
but rather, its opponents eventually die,
and a new generation grows up that is familiar with it,"
Max Planck, German physicist.

INTRODUCTION

Natural gas trapped in shale (shale gas), in sandstone (tight gas) and in coal seams as a product of Hydraulic Fracturing or "Fracking" is asserting a role in North America (USA and Canada), Europe (Poland and Germany), Australia, Indonesia, India, Latin America and Asia (China), as a bridge fuel toward the eventual adoption of renewable and carbon-free sources of energy. Tight natural gas is trapped in rock formations that are about one thousand times less permeable than conventional gas reservoirs and requires the use of hydraulic fracturing for its release. In conventional natural gas deposits, about 80 percent of the gas can be extracted. In the case argillaceous or clayish rock, only 10 to 20 percent of the gas is extractable.

The global reserves of conventional natural gas are estimated as 44,093 exajoules (1 exajoule = 10^{18} Joules) compared with just 17,145 exajoules in crude oil, according to the German Federal Institute for Geosciences and Natural Resources (BGR). Another 34,951 exajoules are available from unconventional sources in shale, sandstone and coal beds, excluding natural gas hydrates and gas from water-saturated rocks. The global primary energy consumption was 470 exajoules in 2009. Natural gas could replace coal as a source of electrical power production by 2030. Half as much CO_2 is emitted in the combustion of natural gas as in coal combustion, with a positive effect on global warming. From a different perspective, global shale oil reserves are estimated at over three trillion barrels recoverable under current technology. The USA has two trillion of those barrels.

Table 1. Global resources of conventional and unconventional natural gas in shale, sandstone and coal beds, excluding gas from water-saturated rocks, in trillion cubic meters. Data: BGR.

Location	Conventional [10^{12} m^3]	Unconventional [10^{12} m^3]
North America	31.2	372.4
Europe	6.3	84.4
Commonwealth of Independent States (CIS)	117.1	248.8
Middle East	35.4	147.7
Latin America	9.4	233.2

Africa	16.2	153.2
Asia/Australia	25.1	480.1
Global	240.6	1,719.8
Global natural gas consumption, 2009	2.9	

Estimates of USA shale gas resources are about 862 trillion cubic feet, and shale contributes 23 percent of the USA natural gas supply, with an expectation that it could reach 46 percent by 2035. Over 3,000 gas wells have been drilled in Pennsylvania in the 2005-2011 period, and 15,000 in north Texas.

In 2013 USA production reached 7.4 million barrels / day, an increase over 2012 of 15.3 percent. In 2014, production should reach 8.3 million barrels / day. The volumes of crude petroleum being moved by train cars, for the lack of existing pipelines from the shale fields, was 9,500 wagons in 2008. In 2013, this number reached 400,000 train cars. For natural gas the output is expected to reach 70 billion cubic feet / day in 2014, reaching over 100 billion cubic feet / day by 2040.

The decades-old secondary recovery technique of hydraulic fracturing is undergoing a dramatic revival and a wide adoption since the introduction of horizontal well drilling in shale formations, but has generated environmental concerns about water contamination because of the chemicals used in the process.

Figure 1. Shale Gas basins in the USA. Source: EIA.

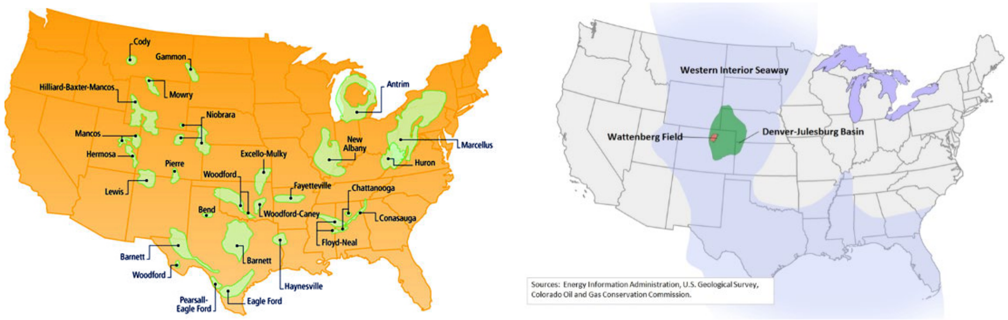

Figure 2. Shale gas occurrences in the USA. Source: USDOE.

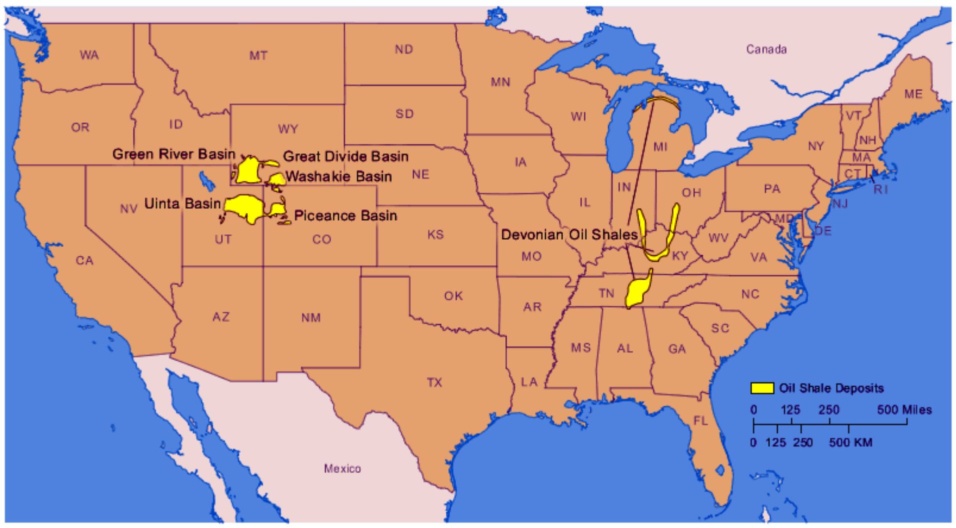

Figure 3. Oil shale deposits in the USA. Source: USDOE.

In terms of water supply usage, the average shale well in the Marcellus Formation uses about 3.8 million gallons of water during the entire operation. This can be compared to 2.2 million gallons per week used by a typical golf course, 5/7 million gallons per minute used by New York City, and 5/11 million gallons of cooling water used by a large coal-fired power plant.

The injected water carries 0.5 percent of sand as a crack propping agent and 0.5 percent as various assisting chemical agents. Tested shale wells identified the following nonspecific chemicals: "pH adjusting agent, corrosion inhibitor, friction reducer, antibacterial agent, scale inhibitor, clay stabilizer, gelling agent, iron control, crosslinker, breaker, acid and surfactant."

Figure 4. Seismic exploration trucks in Bavaria, Germany. Source: DPA.

The USA will overtake Saudi Arabia as the world's biggest oil producer "by around 2020", according to a November 2012 International Energy Agency (IEA) report. The reason for this was the big growth and development in the USA of extracting oil from shale rock. This has enabled the US to gain significantly more extractable oil resources. As a result, the IEA predicts the USA will become "all but self-sufficient" in its energy needs by around 2035. It predicts that the USA will be producing 11.1 million barrels per day by 2020, compared with 10.6 million from Saudi Arabia.

It also expects that the USA will overtake Russia as the world's biggest gas producer by 2015, again thanks to hydraulic fracturing or fracking. It warns that the big growth in USA oil and gas production could have significant geopolitical implications, as it may make the USA less concerned about the Middle East.

Robert A. Hefner III, chairman of The GHK Companies and the author of “The Grand Energy Transition: The Rise of Energy Gases, Sustainable Life and Growth, and the Next Great Economic Expansion,” wrote in an article in August 2014 in “Foreign Affairs*,”* entitled: “The United States of Gas”:

> “Consider how much can change in one year alone. In 2013, on properties in Oklahoma in which the GHK Companies hold interests covering 150 square miles, one large U.S. independent company drilled and completed over 100 horizontal wells. Had those wells been drilled vertically, they would have exposed only about 1,000 feet of shale, whereas horizontal drilling allowed nearly 100 miles to be exposed. And rather than performing the 100 injections of fracking fluid that a vertical well would have made possible, the company was able to perform between 1,000 and 2,000 of them. The company’s engineers also tinkered with such variables as the type of drill bits used, the weight applied while drilling, the rotation speed of the drill, and the size and number of fracking treatments.
>
> Thanks to that continuous experimentation, plus the savings from scale (for example, ordering tubular steel in bulk), the company managed

to slash its costs by 40 percent over 18 months and still boost its productivity. The result: in 2014, six or seven rigs will be able to drill more wells and produce as much oil and gas as 12 rigs were able to the year before. Since the shale boom began, over a decade ago, companies have drilled about 150,000 horizontal wells in the United States, a monumental undertaking that has cost approximately $1 trillion. The rest of the world, however, has drilled only hundreds of horizontal wells. And because each borehole runs horizontally for about one mile (and sometimes even two miles) and is subjected to ten or more fracking injections, companies in the United States have fracked about 150,000 miles of shale about two million times. That adds up to around a thousand times as much shale exposed inside the United States as outside it."

HISTORICAL PERSPECTIVE

EARLY DEVELOPMENT

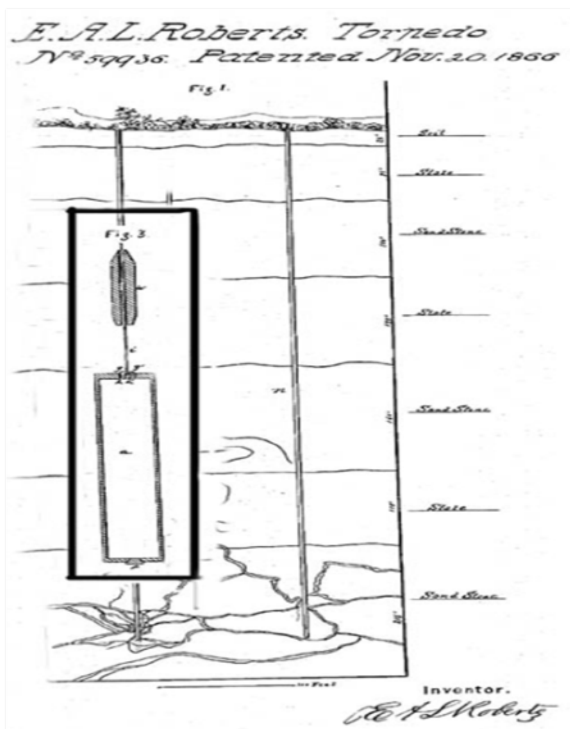

Figure 5. "Torpedo" fracking patent document by Edward A. L. Roberts, 1866.

Hydraulic fracturing technology can be traced back to 1862 during the American Civil War battle of Fredericksburg, Virginia. Colonel Edward A. L. Roberts observed what happens when firing artillery shells into a narrow canal that obstructed the battlefield. The explosion is amplified by the confining canal walls and the generation of steam from the water in what is referred to as "superincumbent fluid tamping."

Colonel Edward A. L. Roberts received his patent on April 26th, 1865, for an "Improvement" in exploding torpedoes in artesian wells. In November, 1866, Edward L. A. Roberts was awarded patent number 59,936, for his "Exploding Torpedo" invention. The process is carried out by packing a torpedo in an iron case that contained 15-20 lbs of explosive black powder. The case is lowered into the depleting well, at a spot closest to the oil. The torpedo is initiated by connecting the top of the shell with an electrical wire to the surface, while filling the borehole with water to generate a steam explosion.

The methodology enhanced the secondary recovery of petroleum by 1,200 percent from some wells within a week of implementation. The "Roberts Petroleum Torpedo Company," charged $100-$200 dollars per rocket, plus a royalty of 1/15 of the profits generated from the enhanced-recovery well.

In the 1930s, drillers used a non-explosive liquid substitute called "acid," instead of nitroglycerin as an explosive, making the created cracks in the medium more resistant to closing, thus increasing productivity. The birth of contemporary hydraulic fracturing began in the 1940s. In 1947, Floyd Farris of Stanolind Oil and Gas carried out a study on the relationship between oil and gas production output, and the amount of pressurized treatment being used on each well. This was followed by the first experiment of hydraulic fracturing at the Hugoton natural gas field in Grant County, Kansas in 1947. In this case, 1,000 gallons of gelled gasoline and sand were injected into a gas producing limestone formation at a depth of 2,400 feet. Afterwards an injection of a gel breaker is done. This experiment failed to produce a significant production increase. However, it marked the start of hydraulic fracturing.

On March 17, 1949, the Halliburton Company conducted two commercial more successful experiments; in Stephens county, Oklahoma, and in Archer County, Texas. In the 1960s Pan American Petroleum began using this drilling technique in Stephens county Oklahoma. In the 1970s, this secondary recovery method was adopted in the Piceance Basin, the San Juan Basin, the Denver Basin, and the Green River Basin.

President Gerald Ford, in the 1975 state of the union address, promoted the development of shale oil resources, as part of his overall energy plan, as a means of reducing foreign oil imports.

RECENT DEVELOPMENT

The recent shale gas technology boosting the USA's natural gas production was initiated in the Barnett Shale deposit in North-Central Texas around Dallas and Fort Worth, Texas, by pioneer George P. Mitchell, who was chairman and chief executive officer of Mitchell Energy and Development Corporation. He perfected the then 40-year secondary recovery method known as "hydraulic fracturing" by combining it with horizontal weel-drilling

In the 1950s, well crews would drop "torpedoes" which are metal cylinders filled with nitroglycerine down the well hole. When the torpedo hits the bottom of the well, it exploded, cracking the rocks and showering everyone within 100 yards with rock chips, water, and oil. Water, sand, and giant pumps have replaced explosive nitroglycerine.

In Wise County, Texas, about 60 miles west of Fort Worth the Greek goat herder named Savas Paraskivoupolis (who changed his name to Mitchell) came to Galveston in 1905. His son George Mitchell worked his way through Texas A&M University and obtained a degree in petroleum engineering. After World War II, George Mitchell teamed up with his brother Johnnie Mitchell and Merlyn Christie. They drilled their first well in 1952, in what became known as the Boonesville Field in Wise County, near Bridgeport. They went on to drill hundreds of gas wells but had to shut them down because they had no way to deliver the natural gas they found in abundance. The work was done at serious financial risk, but they just kept drilling and plugging those wells. Finally a contract for a pipeline was financed by an Illinois utility, and those wells went into production. Mitchell was encouraged by a provision inserted into the 1980 windfall oil profits tax bill to encourage drilling for unconventional natural gas. George P. Mitchell adopted a trial-and-error approach for a long time before succeeding in the late 1990s. The hydraulic fracturing or fracking method that he perfected cracked the rock deep underground, increasing its permeability by opening small cracks that allowed natural gas trapped in tiny pores to flow into the well and up to the surface. Over time, Mitchell would drill over 10,000 wells, with over 1,000 of them being wildcat or exploratory wells.

Devon Energy Corporation, located in Oklahoma, acquired the Mitchell Energy and Development Corporation in 2002 for about $3.3 billion and hybridized the fracking technology with its own directional drilling technology that it developed in offshore exploration to yield a powerful new petroleum and gas production methodology.

The new approach has Devon and its competitors, such as Chesapeake Energy Corporation, SandRidge Energy, and Shell Oil redeveloping old oil and gas deposits such as the Fayetteville Shale in North Arkansas, Haynesville, Marcellus, Woodford, Eagle Ford, Devonian-Mississipian Bakken, and others that were thought depleted.

North Dakota, with its Bakken formation, emerged as the new oil frontier of tight oil and natural gas and became the fourth largest oil producing state behind Texas, Alaska and California. There may be four more layers or benches of shale oil and gas below the Upper Bakken formation, including the promising Three Forks stratum.

Figure 6. Hydraulic fracturing well site.

Figure 7. Hydraulic fracturing rig during and after well completion.

Natural gas is filling a role as a bridge fuel along the road of the implementation of renewable energy sources and an energy economy where hydrogen is used as an energy carrier with fuel cells replacing the Internal Combustion Engine (ICE). Natural gas could be used in the steam reforming process to produce synthetic gas which is a mixture of H_2 and CO. Instead of Carbon Separation and Storage (CCS), the process of carbon dioxide reforming would use natural gas to turn CO_2 into useful products such as green diesel fuel. To overcome the intermittence property of thermal solar energy, the Combined Cycle Concentrated Solar (CCCS) alternative uses natural gas in hybrid plants under construction to provide power during the night period and on cloudy days.

NATURAL GAS COMPARISON TO OTHER FUELS

Natural gas prominently has a high specific energy among existing fuel choices, only exceeded in the energy content per unit weight by nuclear fuel (Table 1). In the last 200 years there has been an evolution toward burning less carbon in favor of burning more hydrogen in different fuels as shown by the atomic ratio of hydrogen to carbon (H / C) in Table 2 for different fuels from wood to natural gas or methane CH_4, as well as its liquid form as methanol or methyl alcohol CH_3OH. The increased per capita energy consumption as estimated by Ausubel [1] is leading to a trend toward using fuels with more hydrogen content as shown in Table 3.

Table 2. Specific energy of different energy supplies.

Fuel	Specific energy [MJ / kg]
Enriched uranium (3-5 percent U^{235})	3.7×10^6
Natural uranium (0.72 percent U^{235})	5.7×10^5
Natural gas	55.6
Diesel fuel	45.8
Crude petroleum	41.9
Coal	32.5
Ethanol	26.8
Wood	10.0

Table 3. Hydrogen to Carbon ratio (H/C) for different fuels

Fuel	Hydrogen to Carbon ratio, (H/C)
Wood	0.1
Coal	0.5-1.0
Oil	0.8-2.0
Light sweet crude oil, $(CH_{1.5})_n$	1.5
Heavy sour crude oil, $(CH_{0.8})_n$	0.8
Clean transport fuel, $(CH_2)_n$	2.0
Cetane, $C_{16}H_{34}$	2.125
Hexane, C_6H_{14}	2.333
Propane, C_3H_8	2.666
Methane, CH_4	4.0
Methanol, methyl alcohol, CH_3OH	4.0
Ethanol, ethyl alcohol, C_2H_5OH	3.0
Hydrogen	Infinity

Table 4. Per capita energy consumption trend for different fuels.

Timescale	Fuel	Per capita consumption in tons of coal equivalent (tce)
1850-1925	Coal	0.3-1.0
1925-2000	Oil	0.8-2.3
2000-2050	Gas	2.0-6.0
2050- …...	Hydrogen	6.0-15.0

However, hurdles have to be overcome along the road. Based on environmental concerns, the province of Québec in Canada, the state of New York in the USA, and France do not authorize the use of the technique of hydraulic fracturing for the extraction of tight natural gas from shale rock formations. Improper application of the technique generated claims that the hydraulic fracturing of tight shale natural gas formations may lead to more environmental concerns than the mining and burning of coal.

In a paper at a conference by the Seismological Society of America in April 2012, researchers from the USA Geological Survey reported that for the three decades until 2000, seismic events in the nation's midsection averaged 21 per year. They increased to 50 per year in 2009, 87 in 2010 and 134 in 2011. The increase is associated with deep disposal well injection of waste water from hydraulic fracturing. There are about 140,000 disposal wells in the USA with a small number associated with potential minor seismic activity.

VERTICAL VERSUS HORIZONTAL DRILLING

In conventional natural gas reservoirs a few vertical wells are usually drilled every 2.5 km^2 and are sufficient to extract the existing natural gas. Tight natural gas formations are porous and have a permeability that is three orders of magnitude lower than the conventional gas reservoirs. Tight gas does not diffuse easily in the low permeability formation rock and is often spread over a larger area.

This necessitates an approach where wells are drilled in different directions from a central location that penetrate the gas reservoir both vertically and horizontally. This poses a limitation on the number of available drilling locations or wells pads on the surface. One of the pretexts used by Iraq's President Saddam Hussein for the invasion of Kuwait in 1990 was that Kuwait was resorting to "slant drilling," whereby its petroleum wells were drilled on Kuwaiti territory, but crossed the border into Iraq underground.

In horizontal drilling, an extensive network of wells is generated, stretching underground for lengths of up to 2 kms or 1.2 miles. This increases the potential production to ten times more than is achieved through conventional methods. Mobile drilling units are moved between the well pads, avoiding the dismantling and reassembling of the drilling equipment for each pad.

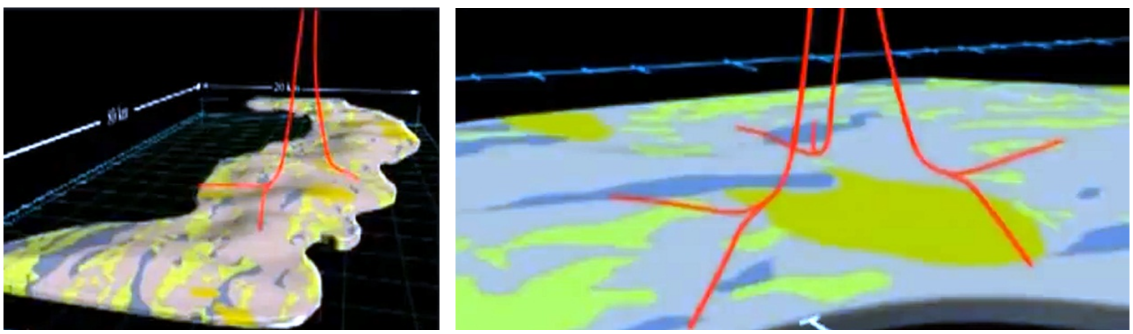

Figure 8. Imaging of multiple horizontal well drilling from a single pad into a tight natural gas shale formation. Source: Royal Shell.

HYDRAULIC FRACTURING, FRACKING

Hydraulic fracturing of tight natural gas shale formations is a secondary recovery drilling technique that involves pumping a mixture of water, sand and chemicals into deep shale deposits to fracture the rock, increase its permeability, and free the oil or gas. The technique has been used since the 1950s, but in the last decade the development of the horizontal drilling technique has made hydraulic fracturing a useful technique. It has allowed the extraction of natural gas from shale rock deposits, which are usually around a mile in depth. The tight natural gas that used to be inaccessible is leading to a substantial increase in natural gas production in the lower 48 USA states.

Figure 9. Blowout preventers (Christmas trees) at Marcellus shale formation, Camptown, Pennsylvania. Source: Southwestern Energy Co,

Figure 10. Blowout Preventer (Christmas Tree) and well casing with associated monitoring instrumentation. Source: Royal Shell.

In hydraulic fracturing, fluids are pumped under high pressure into a well whose casing has been perforated by projectiles shot from a special gun to create fractures in the rock, increasing its permeability. The sand keeps the cracks open after withdrawal of the fracturing fluid and allows the gas to flow into the perforated casing. This takes place deep underground below the shallow fresh water aquifers at pressures sufficient to create fractures in the host rock.

The hydraulic fracturing fluids consist mainly of water mixed with small amounts of chemical additives that help to cool and lubricate the piping and drill bits and prevent scale formation. Sand or ceramic particles are mixed with the fracturing fluid to keep the fractures open and allow natural gas to diffuse through them. Ceramic particles are preferred to sand for shale formations at the greater depths and pressures.

The wells are finished by lining them with steel pipes and are cemented in place down from the surface to below the level of the shallow fresh water aquifer that are the primary sources of the drinking water supplies. When properly installed, these barriers are effective in containing to the hydraulic fracturing fluid and prevent the fluid from mixing with the water in the shallow fresh water aquifers.

INCREASED PRODUCTION AND RESERVES

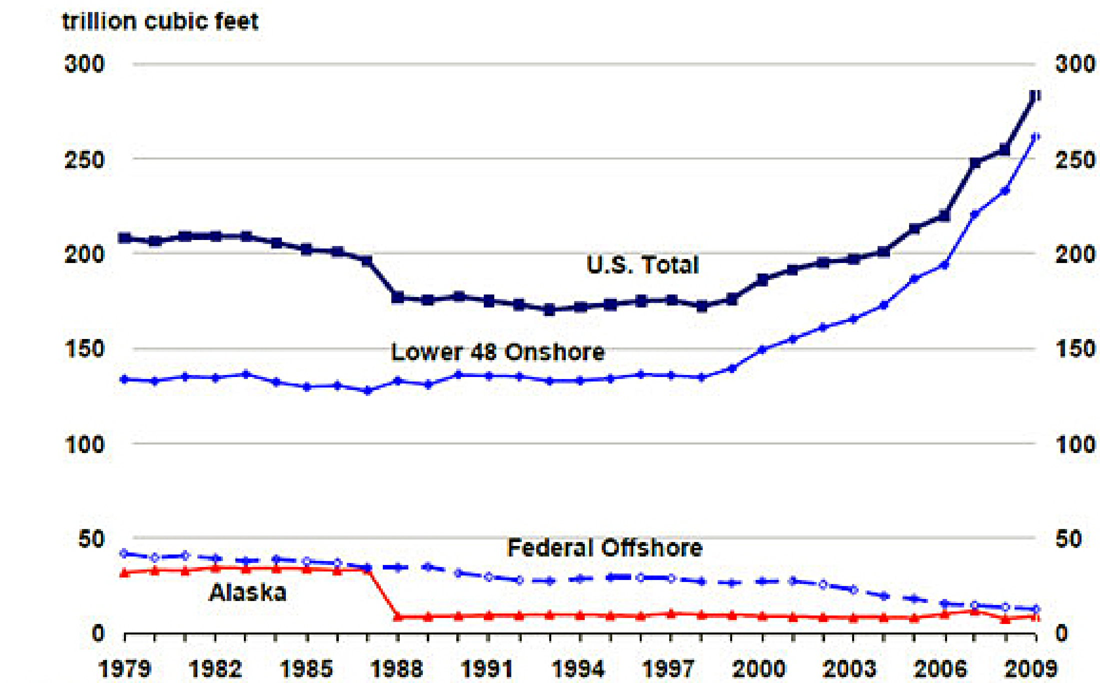

Figure 11. Natural Gas Reserves, USA 1979-2009. Source: USA Energy Information Administration, EIA.

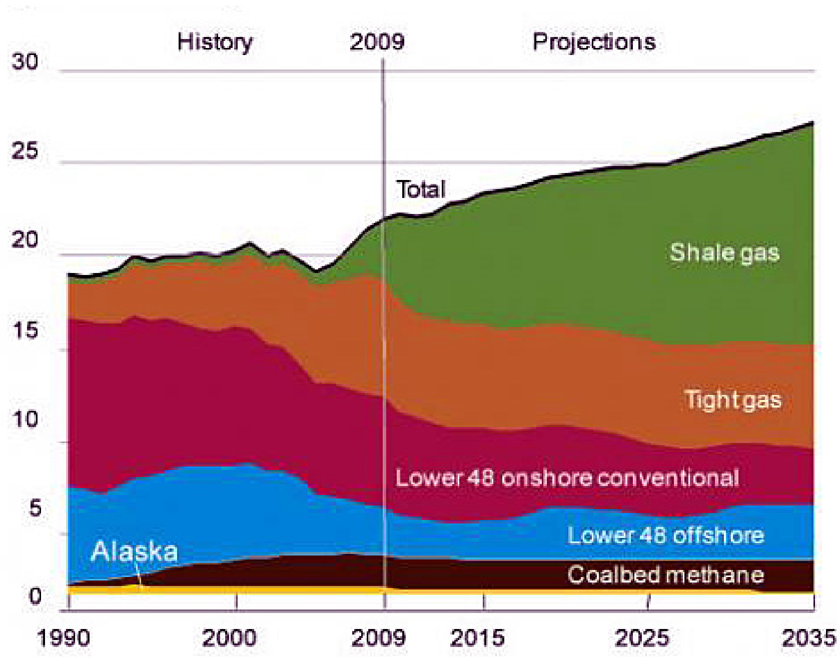

Figure 12. Historic and projected natural gas production projections in trillion cubic feet.

As of 2011, tight shale natural gas deposits are reported to have provided 25 percent of the USA's natural gas production. They are expected to provide 45 percent by the year 2035. In 2010, the USA produced 4.87 trillion ft^3 of shale gas. This represents a 57 percent increase above the 2009 level.

Tight shale natural gas discoveries accounted for 90 percent of the increase in the USA's domestic natural gas reserves in 2009, when gas reserves grew by 11 percent, even as the prices fell by a factor of one third as a result of increased production and supply. Tight shale natural gas currently amounts to 21 percent of the USA's total natural gas reserves.

The increase in tight shale natural gas production was facilitated by the recent developments in the technique of horizontal drilling. The technology advanced to a level where drillers are able to perform the hydraulic fracturing process horizontally. Hydraulic fracturing has been used to extend the lives of vertical wells since 1949, but vertical fracturing cannot retrieve tight shale natural gas at economic levels.

As the global conventional gas fields are suffering depletion, an increase in the price of natural gas occurred and encouraged exploration and capital investment. Hence tight shale natural gas is considered as the "bridge fuel" in the USA's energy plan as it transitions from the depleting hydrocarbons fuels to the renewable energy sources.

TIGHT NATURAL GAS PRODUCTION GOVERNMENT INCENTIVES

President Barack Obama's administration has promoted natural gas as part of its clean energy policy. Yet, earlier support for hydraulic fracturing originated from the time of President George W. Bush's tenure. In 2005, his administration passed the Energy Policy Act, a wide-ranging energy bill championed by his Vice President Dick Cheney.

The Energy Policy Act of 2005 explicitly exempted the hydraulic fracturing process from excessive regulation, specifically the provisions of the Safe Drinking Water Act, the Clean Air Act, and the Clean Water Act. This introduced a loophole that is known as the "Halliburton Loophole," in reference to the previous involvement of Vice President Dick Cheney with the Halliburton Company. It allows the tight gas extraction companies to pump large volumes of hydraulic fracturing fluids into old wells and to store the used fluids in open pools at the surface. In the USA, to provide ample energy supplies, the oil and gas industry is endowed with favorable treatment by being exempt from several provisions in the "Toxic Release Inventory Act," "The Superfund Law," "The National Environmental Policy Act," "Clean Water Act," "Safe Drinking Water Act," and "The Clean Air Act."

About 8 million gallons of water are usually needed to hydraulically fracture a tight natural gas well. A well may be repeatedly hydraulically fractured about 18 times. Each time, about half of the hydraulic fracturing fluid is pumped to the surface entraining the natural gas. The gas is collected at compressor stations, where it is separated from carbon dioxide and compressed for pipeline transport. The returned hydraulic fracturing fluid is either trucked to water treatment plants, injected into old wells, or stored in large, tarp-lined evaporation pools.

ENVIRONMENTAL CONSIDERATIONS

Natural seeps of oil and gas are a common occurrence. Stockton, California lighted its county courthouse in 1854 with natural gas released from a local water well. California has thousands of naturally occurring oil seeps. In the Gulf of Mexico, there are more than 600 natural oil seeps that leak between five hundred thousand and one million barrels of oil per year. When a petroleum seep develops underwater it may form an asphalt volcano. The ecological system has evolved certain bacteria that feed on the oil-seeps hydrocarbon. Oil spills disappear over a few years through evaporation, ultraviolet radiation dissociation and bacterial action.

The rapid growth of hydraulic fracturing has generated opposition due to concerns about shallow fresh water aquifers contamination by the chemicals used in the process. Their leakage is associated with hasty improper or sloppy well finishing and casing procedures. Some of the substances used in the fracking fluids are relatively benign, such as guar gum used to thicken the water-based solution to help transport the "proppant" material; others are more worrisome, like benzene. Poorly constructed wells, improper handling of fluids as they return to the surface or spills can lead to the contamination of the surface water supplies.

Fracking fluids are 90 percent water and 9.5 percent "proppant," such as sand, which helps wedge cracks open. The remaining 0.5 percent of the fluids is a mixture of ingredients:

1. Acids to dissolve minerals and start cracks in the rock,
2. Gelling agents to keep the sand suspended in the solution,
3. Chemical "breakers" to disperse the gel when it is no longer needed,

4. Friction reducers to keep the fluids moving,
5. Biocides to kill off bacteria that corrode the pipes,
6. Other chemicals that stabilize, winterize or neutralize the well.

Naturally occurring radionuclides are unwelcome in fracking fluids that bring them to the surface in drilling operations. When groundwater comes out of a well and it is radioactive above a certain level, they cannot put it back into the ground. Companies have to ship contaminated water to repository sites around the country at very large expense.

The chemicals reportedly used in the process include salt and organic solvents such as benzene and toluene, boric acid, xylene, diesel-range organics, methanol, formaldehyde and ammonium bisulfite. Dilute acids such as hydrochloric or muriatic acid are used to dissolve carbonate minerals and opening fractures near the well bore. Some chemicals are meant to control bacterial growth that could affect the gas and liquid flows as biocides and disinfectants as bromine-based solutions or glutaraldehyde. Scale inhibitors such as ethylene glycol are used to control the precipitation of carbonate and sulfate minerals. Citric acid or hydrochloric acid are used to inhibit the precipitation of iron compounds by keeping them in soluble forms. Friction reducing agents used are potassium chloride or polyacrylamide-based compounds. Corrosion inhibitors such as N,n-dimethyl formamide and oxygen scavengers such as ammonium sulfite are used to protect the well casing. Cross-linking agents that may contain boric acid or ethyl glycol, enhance the capability of the gelling agent to transport the proppant material. A breaker solution is added later to cause the gelling agent to break down into a simpler fluid to be removed from the well bore leaving behind the sand or ceramic proppant material. The use of carbon dioxide fracturing is under consideration as an alternative to water fracturing.

Table 5. Composition of hydraulic fracturing fluids.

Component	Volumetric percentage
H_2O and SiO_2	99.51
Diluted Acid	0.123
Friction reducer	0.088
Surfactant	0.085
Potassium Chloride, KCl	0.06
Gelling agent	0.056
pH adjusting agent	0.011
Breaker	0.01
Cross-linker	0.007
Fe control	0.004
Corrosion inhibitor	0.002
Biocide	0.001

The wells, if improperly finished, are considered eyesores for some. The access roads, storage tanks and drill pads construction have affected pristine tracts of land. The real concern is water contamination. Incidents of fresh water supplies being contaminated by metals and volatile organic compounds as a result of improper hasty well finishing and casing have generated complaints about health problems for people, livestock and wildlife.

Table 6. Hydraulic fracturing additives [8].

Additive	Composition	Function
Diluted Acid	HCl or muriatic acid	Dissolve minerals and initiate cracks in rock
Biocide	Glutaraldehyde	Inhibits bacteria in the water that produce corrosive byproducts
Breaker	Ammonium persulfate	Leads to a delayed break-down of the gel polymer chains
Corrosion inhibitor	N,n-dimethyl formamide	Prevents corrosion of well pipe
Cross-linker	Borate salts	Maintains fluid viscosity at higher temperature
Friction reducer	Polyacrylamide	Minimizes friction between the fluid and the pipe
	Mineral oil	
Gelling agent	Guar gum or hydroxyl ethyl cellulose	Thickens the water to suspend the sand
Iron Control	Citric acid	Prevents precipitation of metal oxides
KCl	Potassium chloride	Creates a brine carrier fluid
Oxygen scavenger	Ammonium bisulfite	Removes oxygen from the water to protect the pipe from corrosion
pH adjusting agent	Na or K carbonate	Maintains the effectiveness of other components, such as cross-linkers
Proppant	Silica, quartz sand	Allows the fractures to remain open so the gas can diffuse out of the well
Scale inhibitor	Ethylene glycol	Prevents scale deposits in the piping
Surfactant	Isopropanol	Increases the viscosity of the fracture fluid

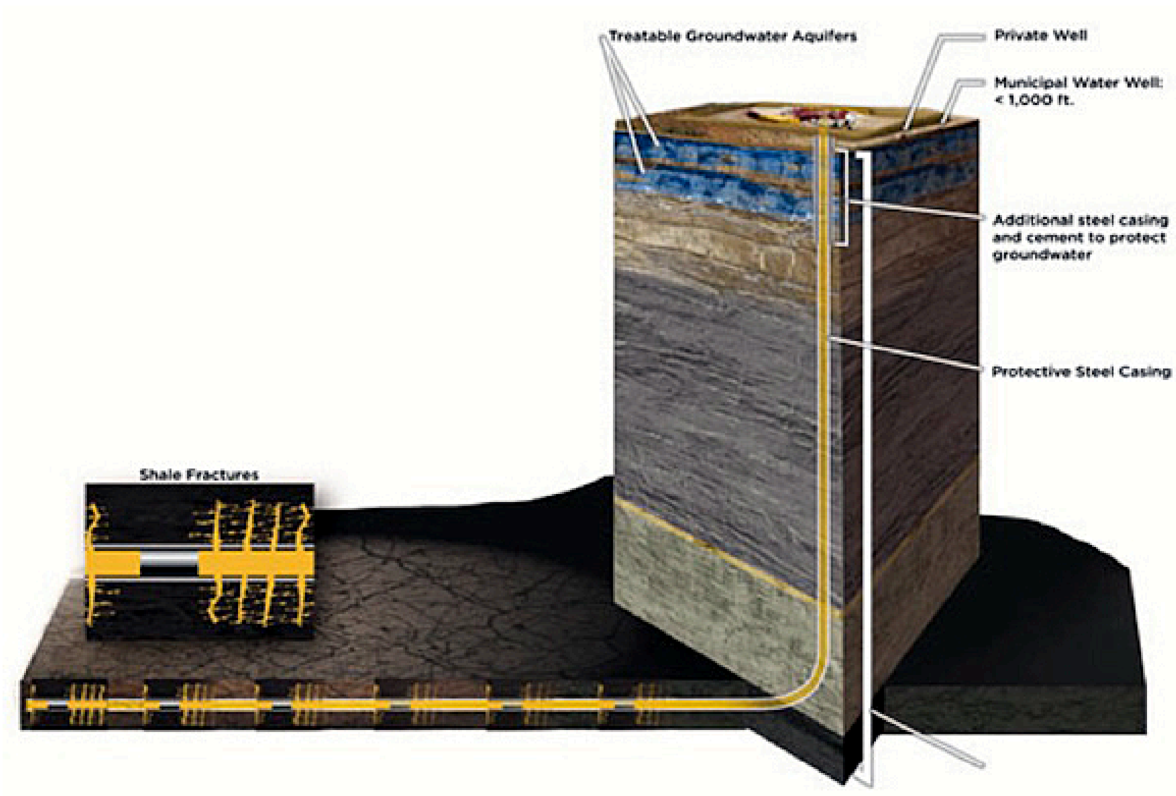

Figure 13. “Jewels” are about four-foot-long sliding sleeves encased in stainless steel, looking like shiny gems along the dark string of iron pipe. To maximize the fracking effectiveness in a two-mile pipe, about 30 sliding sleeves are used. The closed sliding sleeves are included at a set spacing in the steel casing at the time it is set in place. The bottom sliding sleeve is first opened and the first stage is pumped. The next sleeve is opened which concurrently isolates the first stage, and the second stage is pumped, and so on, one stage at a time.

Figure 14. Fracturing gun and generated fractures around horizontal well bore.

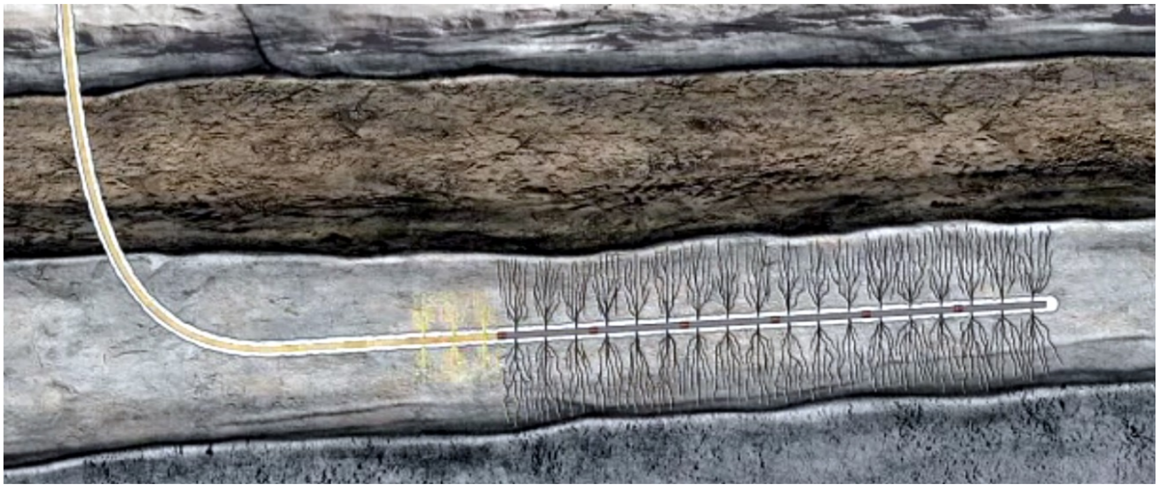

Figure 15. Fractured horizontal well shale formation.

In the state of Pennsylvania, the Department of Environmental Protection reported an incident involving the contamination of the fresh water aquifer feeding rural household wells in Dimrock after more than 60 wells were drilled in a 9 square-mile area. The hydraulic fracturing operations may have caused the water to turn brown in color and imbued it with methane (CH_4) gas, iron and aluminum. Hydraulic fracturing fluids leaked into water streams, affecting their colors and killing fish. The methane in a water well ignited and caused an explosion. A family evacuation was initiated because of hazardous methane levels at their home.

Tight shale natural gas formations are typically 5,000-8,000 feet in depth. This is below the fresh ground water aquifers that exist up to 1,000 feet in depth. Consequently, it is not plausible that the hydraulic fracturing gases and fluids diffuse all the way up to the aquifers through fractures. Contamination can more likely be attributable to hasty poor cementing and well casings that would cause the hydraulic fracturing fluids and methane gas to escape at the shallow fresh water aquifers level.

The so-called Halliburton Loophole exempts hydraulic fracturing from otherwise restraining regulations. The above-ground handling of return hydraulic fracturing water and the airborne pollution produced through processing are perceived as sources of health risks in the hydraulic fracturing process. The city of Fort Worth, Texas, sits atop a productive tight natural gas shale formation. The chemical emissions from the natural gas processing facilities at Fort Worth are reported as equal to the city's total emissions from automobiles and trucks.

The Eagle Ford shale formation holds an estimated 3 billion barrels of oil and 150 trillion cubic feet of natural gas reserves. The formation stretches from north Houston, Texas, southwest to the Mexican border. The shale's existence was known for a generation of geologists. However, the techniques for extracting oil and gas from it have become practical in the last decade. The first Eagle Ford well was drilled in 2008. The Eagle Ford formation could provide as many as 900,000 barrels per day by 2016. The Permian Basin, deep in west Texas, may reach 1 million barrels daily. By 2020, Texas' crude output may exceed the 3.45 million barrels a day seen in 1972 if prices stay high enough to make drilling economical. The Eagle Ford oil output rose to more than 352,000 barrels a day in 2012, compared with 358 barrels a day in 2008. The number of drilling permits surged to 4,143 in Eagle Ford in 2012, up from just 26 in 2008. Mineral rights are assigned for $1,500 per acre over a 5-million-acre territory, yielding $7.5 billion in compensation since 2007 [9].

SAFETY CONSIDERATIONS

GENERAL PROVISIONS

Safety procedures are applied in the hydraulic fracturing process according to the "as reasonably as practicable" industry and regulatory principle. Professionally conducted hydraulic fracturing engineering operations incorporate electronic monitoring equipment measuring the wells parameters to ensure its safe operation. Pressure sensors are used to check that the wells are firmly sealed. The fractures and the fluids are also monitored.

Hydraulic fracturing technology was developed in the 1940s and has been continuously improved. Advanced sensors record what happens when the shale formation rock is fractured. Imaging software using virtual reality methods and specialized computers is used to map the gas fields below the surface to better target the gas-bearing formations.

In the USA, about one million hydrocarbon wells have been hydraulically fractured since the process was first introduced. However, local communities are becoming concerned over the increase production activities and fracturing. Studies by the USA Environmental Protection Agency (EPA) and the Ground Water Protection Council have determined that the process can be safely conducted.

Figure 16. Mixing water and sand at a 6,600 psi pressure. Marcellus formation, Camptown, Pennsylvania. Hydraulic fracturing is being used to pump natural gas out of about 3,000 wells in the USA, with 120 to 150 wells being added every month. The actual procedure lasts only about a week, and then the operating team moves on to the next on a long list of wells. Source: Southwestern Energy Co.

Figure 17. Hydraulic fluid recycling.

Before drilling a well, a set of practices, called a “safety case,” is used to analyze the anticipated risks and to develop protective barriers over the operational lifetime of the well. Two or more barrier layers are built into all oil and gas wells and for the surface storage enclosures of the fluids produced from the wells. Steel casings and cement is used to protect and isolate the potable fresh groundwater zone from the production stream, as well as from the hydraulic fracturing fluids, in the wellbore.

The use of open pit systems for the primary containment of the produced and drilling fluids is being phased out in several operating areas. The released information about the chemicals used in the hydraulic fracturing operations is still incomplete and sketchy and is considered as proprietary information by the suppliers.

Monthly safety reviews of the processes are conducted. Emergency response plans that take into account the local surroundings are put in place.

WATER USAGE ISSUES

The completion and production activities are designed in such a way so as to isolate them from the potable groundwater aquifers. Only air, water, or water-based drilling mud is used through and to at least 500 feet or 150 meters below the potable groundwater aquifers. This particular zone is carefully cemented and cased before drilling further or hydraulic fracturing is carried out at the lower levels of the wells.

Figure 18. Sand and water mixing at the Marcellus formation, Camptown, Pennsylvania. Trucks bring giant 2,400 horsepower pumps to the site, where about a dozen of these are connected. A fluid and sand mixture at about 1,000 bar is forced into the deposit. The mixture consists of millions of liters of water, special sand and chemicals designed to kill bacteria that could inhibit the flow of gas. Source: Bloomberg.

In new potential development areas, the potable fresh groundwater is tested before and after drilling to help determine whether changes have occurred as a result of the hydraulic fracturing activities. The use of potable fresh water is minimized and non-potable water supplies are used whenever available. The hydraulic fracturing and completion fluids are pumped back to closed systems or tanks. The fracturing fluid and produced water that comes out of the well are recycled to the extent possible in the field. It is stored, treated and disposed of it in an environmentally responsible manner and in accordance with the prevailing regulatory requirements.

EMISSIONS CONTROLS

Emissions are minimized according to the "as reasonably as practicable" operational principle. The emissions are measured, catalogued and reported to the appropriate regulatory agencies. Fugitive emissions are detected by visual observation and infrared testing. Routine venting is eliminated if permitted; wherever venting is required by regulation. Vapor recovery units are usually used at the wellheads.

Steps to lower emissions from the operations include the use of natural gas engines. Catalyst technology used in diesel cars and power plants can be used on drilling rigs in harsh winter environments. The catalyst can reduce the local emissions from the drill rig engines by about 90 percent.

Natural gas is considered as a clean and green fuel because, on combustion, it emits roughly half the carbon dioxide of coal and about 30 percent that of petroleum. The problem is that its combustion is only one part of the natural gas life cycle. During other parts of the cycle, methane CH_4 could be released to the environment. Cornell University studies suggest that the rush to develop the USA's unconventional gas resources will likely increase the nation's carbon emissions rather than decrease them. The suggestion is that between 3.6 - 7.9 percent of the CH_4, a greenhouse gas, is lost from the time a well is plumbed to when the gas is used.

A study from the Goddard Institute for Space Studies at NASA suggests an interaction between CH_4 and certain aerosol particles significantly amplifies its already potent greenhouse gas effects.

A large fleet of trucks drive around to bring the hydraulic fracturing fluids to drills and to remove the waste water. When this is factored in, the greenhouse gas footprint of shale gas is suggested to be 20 percent greater than coal per unit of energy content, and estimated to be twice as high. Such an impact needs to be minimized by judicious engineering, as well as the effect of the operations on wildlife and livestock, such as limiting the activities during specific time periods.

The landscape is to be restored once a drilling location is completed in collaboration with the Bureau of Land Management such as planting a mix of native species trees, brushes and grasses that are food staples to the local fauna.

Figure 19. Water treatment plant for the separation of oil, sediment and antifreeze, Camptown, Pennsylvania, Marcellus formation. Source: Bloomberg.

ECONOMICAL ATTRACTIVENESS

Hydraulic fracturing enjoys wide ranging industry and landowners support in the USA. In the USA, landowners in most locations also own the mineral rights below their land, which is not generally the case in Europe. The royalties and lease fees that the drilling companies pay to the landowners are sufficient to turn them into ardent supporters. The price to lease an acre of the Marcellus Shale, the shale formation stretching from West Virginia to New York, continues to climb. Twenty years ago around 1990, it was just $25/(acre.year). As of 2012, it averages $5,000/(acre.year). The industry creates a large pool of local jobs and injects funds into the local communities and state economies.

COMPARISON TO SHALE AND SHALE OIL DEPOSITS

Tight natural gas shale deposits should be distinguished from shale and shale oil deposits. Shale may contain organic matter, but no oil. Some occurrences of petroleum do occur in shale oil deposits. However, there was not enough time, pressure and heat to generate oil in the oil shale. The process of forming oil must thus be completed by heating the organic matter in the oil shale first using an energy source as heat, often with the addition of water; at a significant cost.

In shale oil deposits, oil has already been generated but is trapped in the dense fabric of the rock. Its extraction from the rock matrix is more difficult than from the conventional porous rock reservoirs since the petroleum has not been expelled from the shale and did not migrate away from the source shale rock into the porous rock such as sandstone. In this case one needs to help the process of migration by fracturing the shale.

GLOBAL CONSIDERATIONS

Figure 20. Liquefied natural gas tanker. Source: Reuters.

The natural gas's share of the energy mix worldwide is growing and the fuel will become more important. Gas turbines and combined cycle power plants are becoming more common, replacing old coal plants. They would be the ideal supplement to a fluctuating flow of energy from renewable sources. Natural gas offers new prospects as a fuel. In the USA truck fleets are being converted to liquefied natural gas.

Figure 21. Hydraulic fracturing rigs in Poland. New drilling rigs can move themselves and drill as many as 16 holes from one pad, into all the various levels and in different directions.

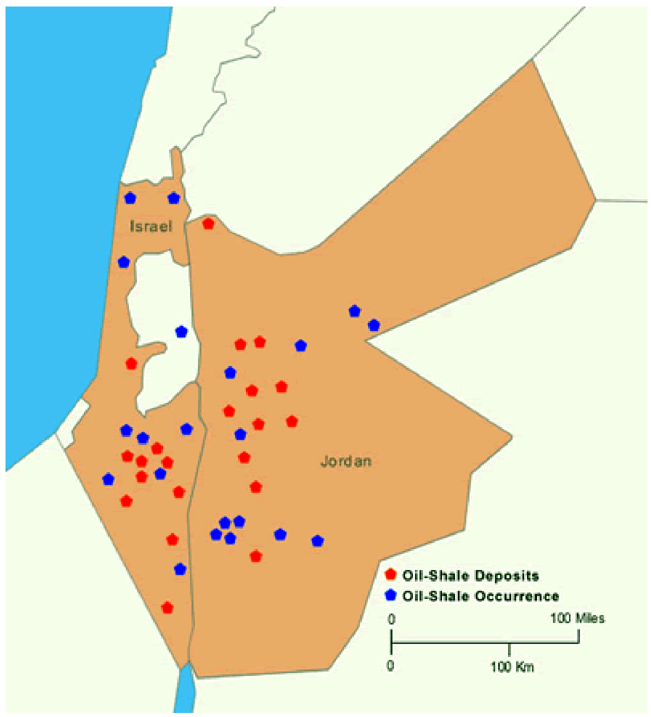

Figure 22. Oil shale prospects in Jordan and Israel.

UPPER DEVONIAN-LOWER MISSISSIPIAN BAKKEN-LODGEPOLE SHALE FORMATION, WILLINSTON BASIN PROVINCE

The USA Geological Survey (USGS) estimates that the states of North Dakota and Montana have 3.0-4.3 billion barrels, with an average of 3.65 billion barrels, 1.85 trillion cubic feet of associated/dissolved natural gas, and 148 million barrels of natural gas liquids, of undiscovered, technically recoverable hydrocarbons in the area known as the Bakken Formation. This is a 25-fold increase in the amount of oil that can be recovered compared to a 1995 estimate of 151 million barrels of oil. Technically recoverable oil resources are those producible using currently available technology and industry practices.

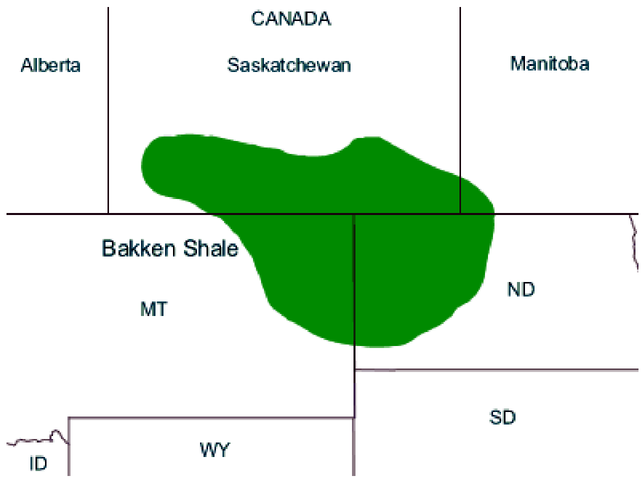

Figure 23. Extent of the Bakken formation in the USA and Canada. Source: USGS.

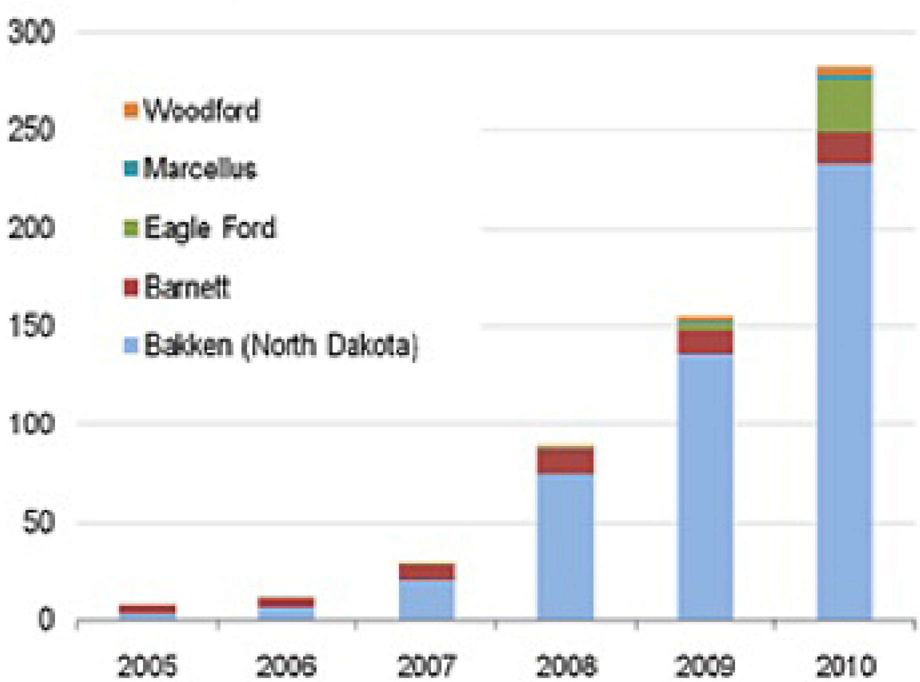

Figure 24. Oil production from shale formations in thousands of barrels per day.

The Upper Devonian-Lower Mississippian Bakken Formation is a thin and widespread unit within the central and deeper portions of the Williston Basin in Montana, North Dakota, and the Canadian Provinces of Saskatchewan and Manitoba. The formation consists of three members:

1. A lower shale member,
2. A middle sandstone member,
3. An upper shale member.

In the Bakken-Lodgepole Total Petroleum System (TPS), the upper and lower shale members of the Bakken Formation are the source for oil produced from reservoirs of the Mississippian Lodgepole Formation.

Each succeeding member is of greater geographic extent than the underlying member. The upper and lower shale members are composed of organic-rich marine shale of fairly consistent lithology; they are the petroleum source rocks and part of the continuous reservoir for hydrocarbons produced from the Bakken Formation. The middle sandstone member varies in thickness, lithology, and petro-physical properties, and local development of matrix porosity enhances oil production in both continuous and conventional Bakken reservoirs.

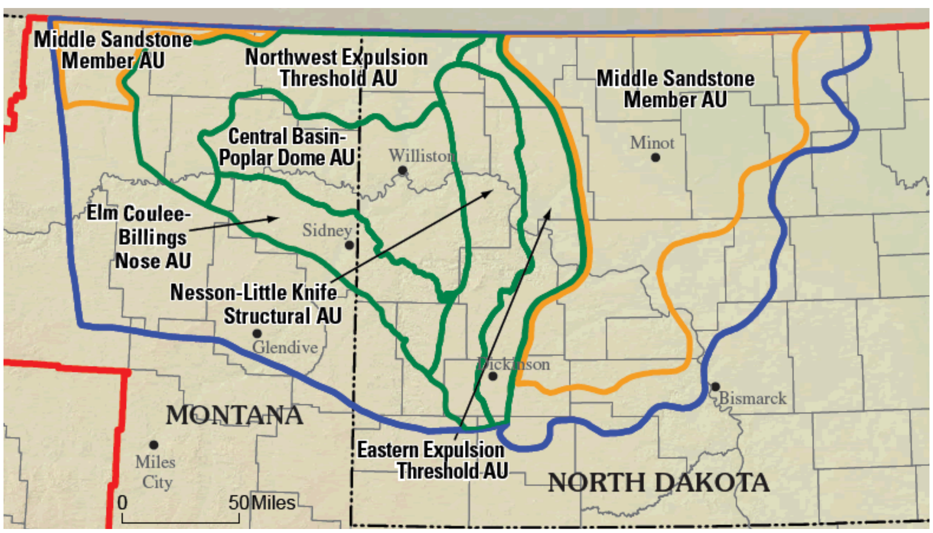

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Figure 25. USA Bakken-Lodgepole formation Total Petroleum System (TPS) (blue), five Assessment Units (AUs) (red), one conventional AU (orange), area of oil generation for the upper shale member of the formation (green). Source: USGS.

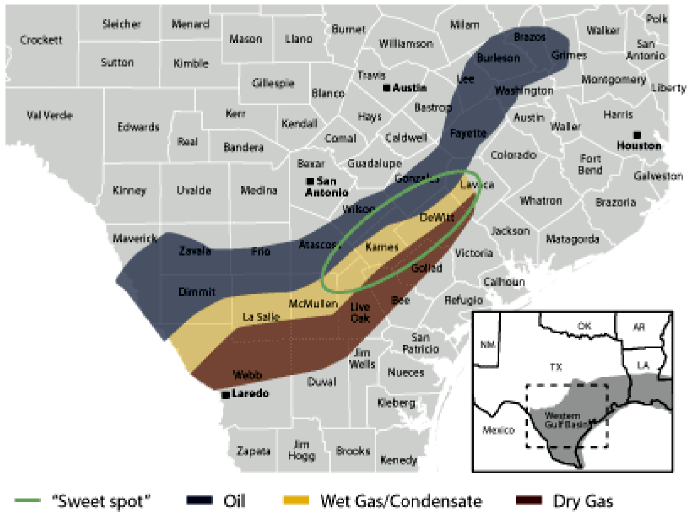


Figure 26. The Eagle Ford formation in Texas.

The Bakken Formation estimate is larger than all other USGS oil assessments of the lower 48 states and is the largest "continuous" oil accumulation ever assessed by the USGS. A "continuous" oil accumulation means that the oil resource is dispersed throughout a geologic formation rather than existing as discrete, localized occurrences. The next largest "continuous" oil accumulation in the USA is in the Austin Chalk of Texas and Louisiana, with an undiscovered estimate of 1.0 billion barrels of technically recoverable oil.

Five continuous Assessment Units (AU) were identified in the Bakken Formation of North Dakota and Montana at: the Elm Coulee-Billings Nose, the Central Basin-Poplar Dome, the Nesson-Little Knife Structural, the Eastern Expulsion Threshold, and the Northwest Expulsion Threshold.

A number of wells have produced oil from three of the assessments units in the Central Basin-Poplar Dome, the Eastern Expulsion Threshold, and the Northwest Expulsion Threshold. The Elm Coulee oil field in Montana, discovered in 2000, has produced about 65 million barrels of the 105 million barrels of oil recovered from the Bakken Formation.

It must be observed that the Bakken bump could produce as much as 2 million barrels per day (bpd) up from roughly 500 thousand bpd, maybe as much as 3 million bpd, but the USA imports roughly 8 million bpd today under even severe economic conditions, and as much as 10 million bpd under happier economic conditions. The Bakken and other shale plays are simply not going to replace all of that. The gains realized from shale oil are fighting depletion losses from the rest of the tired fields under production. Typical petroleum wells in the Bakken formation initially produce 200 barrels per day and decline 70-75 percent in the first year to a flat 30-40 barrels per day. Conventional wells produce oil with a fast ramp up to several thousand barrels/day and can hold that or decline slowly for 10 years at 5 percent/yr. It must be admitted that the cost of production from the Bakken fields is much higher than traditional oil cases using vertical oil wells that produce 1,000-10,000 barrels per day.

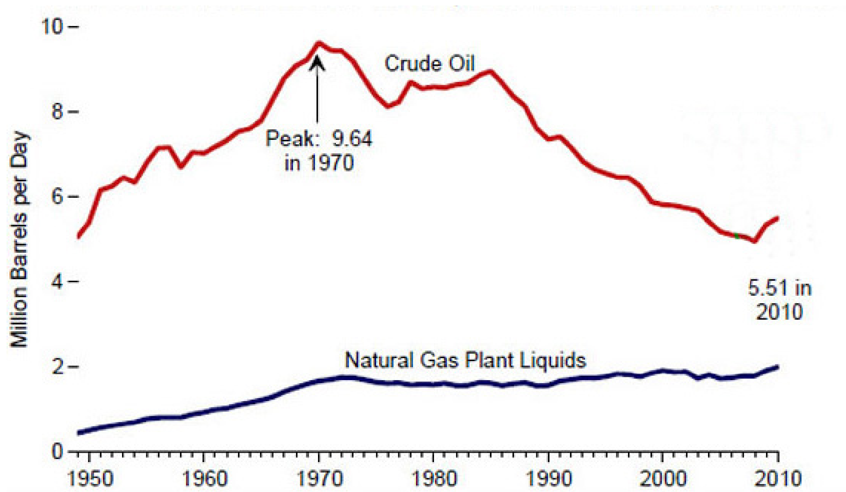


Figure 27. USA crude petroleum and natural gas liquids field production showing the 2010 "Bakken Bump," over the period 1949-2010. Source: EIA.

NATURAL GAS AND THE HYDROGEN ECONOMY

The USA uses some 10 x 10^6 tons /year of hydrogen for industrial purposes, such as manufacturing fertilizer and refining petroleum. If hydrogen-powered vehicles are to come into use the need would increase to 10 times the current usage.

Figure 28. Hydrogen station at Burlington, Vermont. Source: DOE.

STEAM METHANE REFORMING, SMR

Fossil fuels are also considered as "hydrocarbons" and hence contain hydrogen in addition to carbon. About 95 percent of the USAs hydrogen is produced from natural gas through a process called Steam Methane Reforming (SMR).

High temperature and pressure break the hydrocarbon into hydrogen and carbon oxides including carbon dioxide, which is released into the atmosphere as a greenhouse gas.

Over the next 10-20 years, fossil fuels are expected to continue to be the main feedstock for the hydrogen economy. Using fossil fuels energy to make clean energy does not solve the CO_2, SO_x and NO_x, mercury, arsenic, cadmium and even radioactive pollution problems associated with fossil fuels.

A partial remedy is Carbon Capture and Sequestration (CCS) which involves capturing the generated CO_2 and sequestering it underground to make the process more environmentally friendly. The General Electric Company (GE) and British Petroleum (BP) announced plans to develop as many as 15 power plants that will strip hydrogen from natural gas to generate electricity. The waste CO_2 would be pumped into depleted oil and gas fields.

The USA Department of Energy (USDOE) is considering funding a 10-year, $950 million project to build a coal-fed plant that will produce hydrogen to make electricity, and likewise lock away CO_2 to achieve what it bills as "the world's first zero-emissions fossil fuel plant."

Hydrogen gas can be produced in gas station-size facilities using natural gas steam reforming. There would be a need for 15.9 million ft^3 / year, which is a fraction of the current USA annual natural gas consumption. A number of 777,000 small distribution facilities would be needed with a number of large central production plants.

Table 7. Comparison of different sources of hydrogen as transportation fuel. Hydrogen production: 150×10^6 tons /year.

	Nuclear Fission	Wind Power	Solar Power	Natural Gas	Biomass	Coal
Total cost [$ trillion]	0.84	3.0	22.0	1.0	0.565	0.500
Price per gallon of gasoline equivalent [$ /gce]	2.5	3.0	9.5	3.0	1.9	1.0
CO_2 emissions [million tons]	0	0	0	300	600*	600**

* Zero net emissions.
** With 90 percent CO_2 capture and underground storage.

Uncertainties still exist about the CO_2 containment in large scale operations. Natural gas is a limited resource whose price fluctuation would affect the cost of the produced hydrogen.

The Steam Methane Reforming (SMR) process is the most widespread method to generate hydrogen-rich synthesis gas from light hydrocarbons. The feed material can be natural gas, liquid gas or naphta. They are converted endothermically with steam into synthesis gas in catalytic tube reactors. Process heat as well as flue gases are used for the generation of steam.

The process consists of three main steps:

1. **Reformation process**

The first step of the SMR process involves a light hydrocarbon reacting with steam at 750-800°C or 1,380-1,470ºF to produce a synthesis gas or syngas, which is a mixture primarily made up of hydrogen, H_2 and carbon monoxide, CO.

The desulfurized hydrocarbon feed is mixed with superheated process steam in accordance with the steam/carbon relationship necessary for the reforming process. This gas mixture is heated up and then distributed on the catalyst-filled reformer tubes. The gas mixture flows from top to bottom through tubes arranged in vertical rows. While flowing through the tubes heated from the outside, the hydrocarbon/steam mixture reacts, forming hydrogen and carbon monoxide according to:

$$C_nH_m + nH_2O \rightarrow nCO + \frac{(2n+m)}{2}H_2 \qquad (1)$$

2. Shift Reaction

The second step, known as a Water Gas Shift (WGS) reaction, the CO produced in the first reaction is reacted with steam over a catalyst to form H_2 and CO_2.

This process occurs in two stages, consisting of a High Temperature Shift (HTS) at 350 ºC or 662 ºF endothermic reaction:

$$CH_4 + H_2O \rightleftarrows CO + 3H_2 \qquad (2)$$

and a Low Temperature Shift (LTS) at 190-210 ºC or 374-410 ºF exothermic reaction:

$$CO + H_2O \rightleftarrows CO_2 + H_2 \qquad (3)$$

To minimize the CH_4 content in the synthesis gas while simultaneously maximizing the H_2 yield and preventing the formation of elemental carbon and keeping it from getting deposited on the catalyst, the reformer is operated with a higher steam/carbon relationship than theoretically necessary.

As the process is endothermic, the required heat must be produced by external firing. The burners for the firing are arranged on the ceiling of the firing area between the tube rows and fire vertically downward. The residual gas from the pressure swing adsorption unit as well as heating gas from battery limits is used as fuel gas. The flue gas is then cooled down in a convection zone, generating steam.

3. Purification Process

High to ultra-high purity hydrogen is needed for the durable and efficient operation of fuel cells. Impurities are believed to cause various problems in the current state-of-the-art fuel cell designs, including catalyst poisoning and membrane failure. Additional process steps may be required to purify the hydrogen to meet industry quality standards.

Additional steps could also be needed if carbon capture and sequestration technologies are developed and utilized as part of this method of hydrogen production. Hydrogen produced from the SMR process includes small quantities of CO, CO_2, and HS as impurities and requires further purification. The primary steps for purification include:

1. Feedstock purification: This process removes toxic substances, including sulfur (S) and chlorine (Cl), to increase the life of the downstream steam reforming and other catalysts.
2. Product purification: In a liquid absorption system, CO_2 is removed. The product gas undergoes a methanation step to remove residual traces of the carbon oxides. Recent SMR plants utilize a Pressure Swing Absorption (PSA) unit instead, producing 99.99 percent pure product hydrogen.

DRY CO_2 REFORMING PROCESS

Synthesis gas (syngas), is a mixture of H_2 and CO and is a building block for several important chemicals.

The CO_2 dry reforming of natural gas produces syngas from the equation [2]:

$$CO_2 + CH_4 \rightarrow 2CO + 2H_2 \tag{4}$$

Syngas can be produced by reforming natural gas with CO_2 or steam. Partial oxidation of natural gas and heavier hydrocarbon feed-stocks is another means of producing syngas.

Reforming of natural gas with CO_2 can produce syngas with a H_2/CO ratio of unity at 1,652-1,832°F (900-1,000°C) and 1-20 atmosphere pressure.

Group VIII metals such as nickel, Co, rhodium and ruthenium or Mo_2C are suitable as catalysts for natural gas CO_2 reforming. Nickel has a high tendency of coking under most reforming conditions, but is still a preferred option. Palladium and platinum offer a compromise between costs and good functionality.

Alumina, magnesia, silica, zirconia, and titania have been considered as support structures to the catalysts. Syngas can be produced with imported CO_2 or from captured and recycled CO_2. Syngas itself can then be converted into other products such as methanol, sulfur-free green diesel fuel and carbon.

HIGHER VALUE PRODUCTS

Synthesis gas is an equimolar mixture of CO and H_2. By adding H_2 to the reactant gas feed to establish the correct reactants ratio, it can be used to produce higher value products, most notably sulfur-free diesel using the Fischer-Tropsch process:

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O \tag{5}$$

It can also be used to produce methanol:

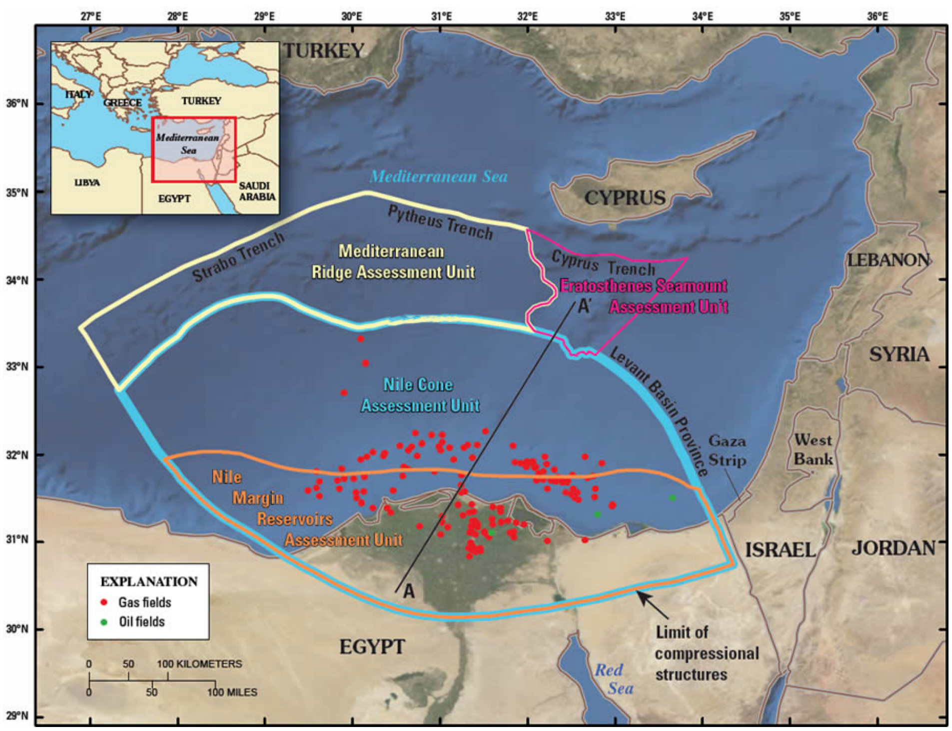
$$CO + 2H_2 \rightarrow CH_3OH \qquad (6)$$

The required additional H_2 could be supplied by the steam reforming of CH_4 through the reaction:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (7)$$

The dry reforming reaction is highly endothermic and so energy has to be supplied to drive it. Methanol is produced by the Synetix or ICI process in the temperature range 473-573 K, while reforming reactions are usually carried out in the temperature range 973-1,223 K.

INTEGRATED SOLAR COMBINED CYCLE (ISCC)



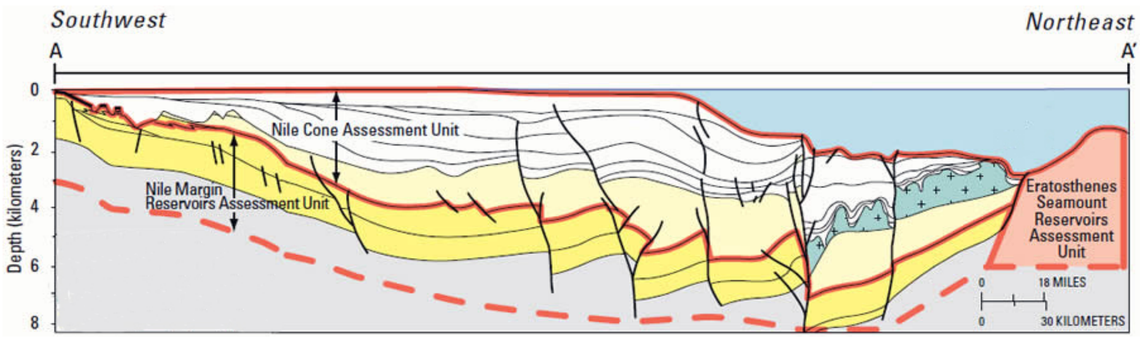


Figure 29. Nile delta gas resources. Source: USGS.

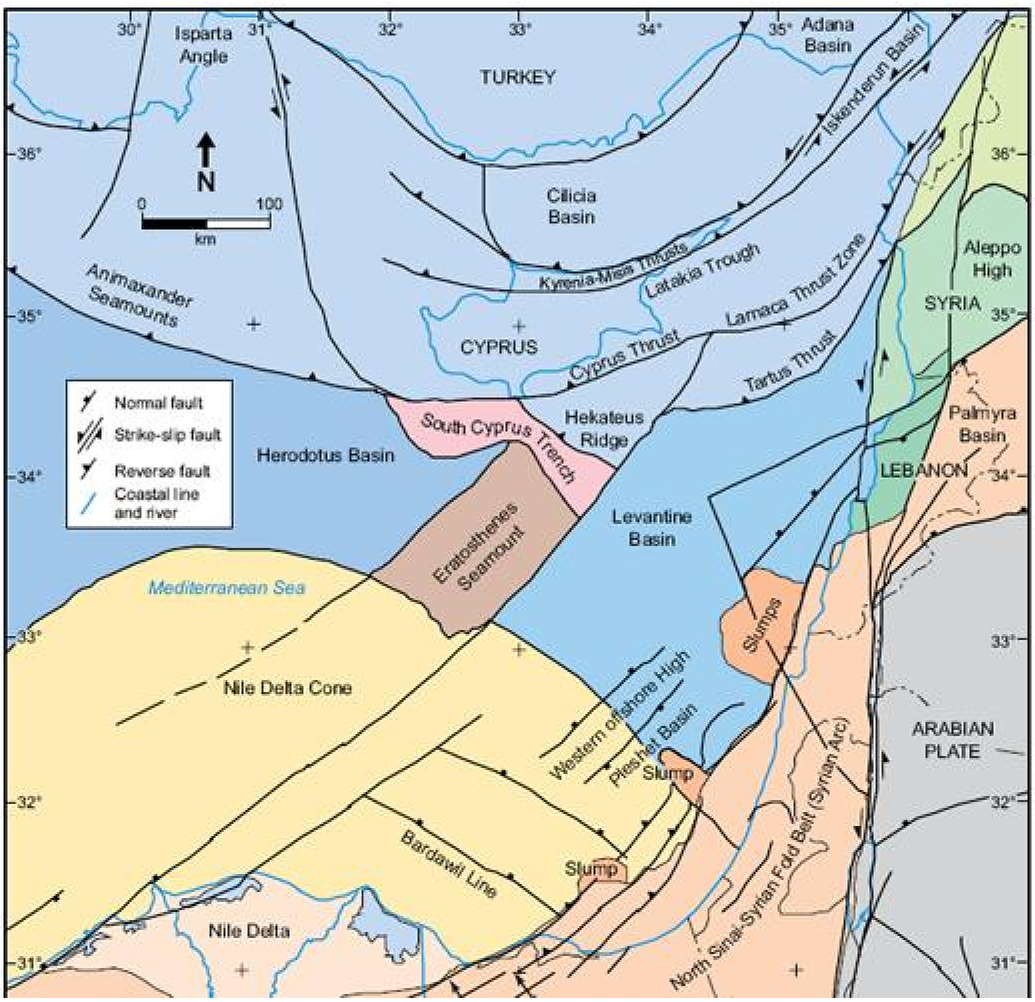


Figure 30. Levantine Basin gas resources. Source: USGS.

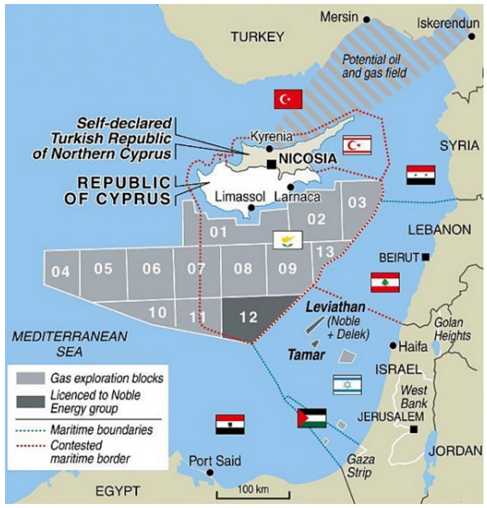


Figure 31. Natural gas fields in Eastern Mediterranean. Source: AFP.

Conceptual plant designs with energy storage as well as supplemental heating to enhance the capacity factor as well as avoid the thermal cycling problem encountered in solar-only plants are under construction or in the design stage.

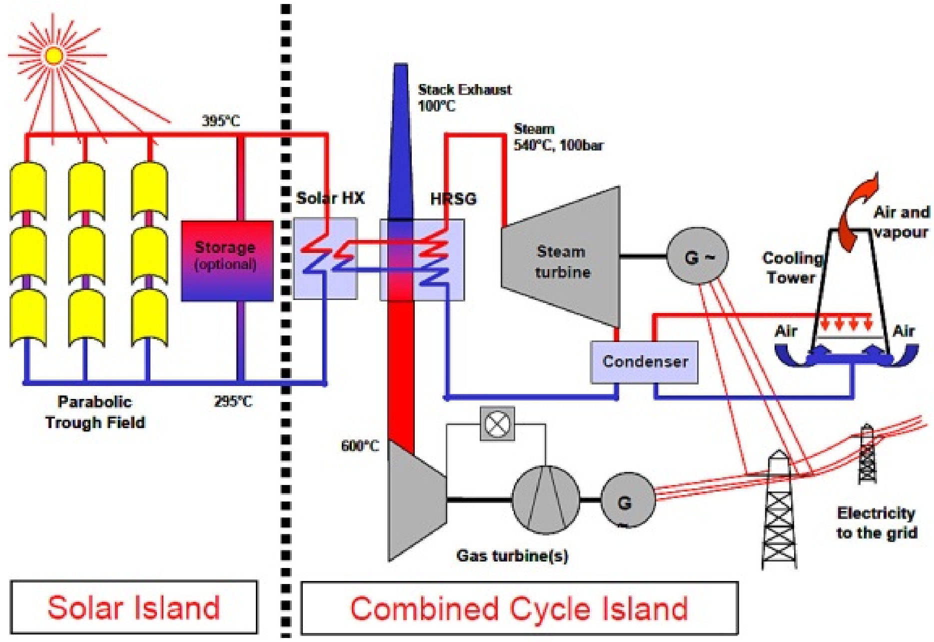


Figure 32. Integrated Solar Combined Cycle (ISCC) power diagram, Al Kuraymat, Egypt.

A world competition is ongoing on plans for the world's largest solar thermal power plant. The United Arab Emirates (UAE) is joining the fray with a massive concentrated solar energy project called Shams-1 or Sun-1, in Arabic.

The Masdar Company is teaming up with French oil company Total and Spanish solar company Abengoa Solar to build a 100 MW solar plant outside of Abu Dhabi in the UAE.

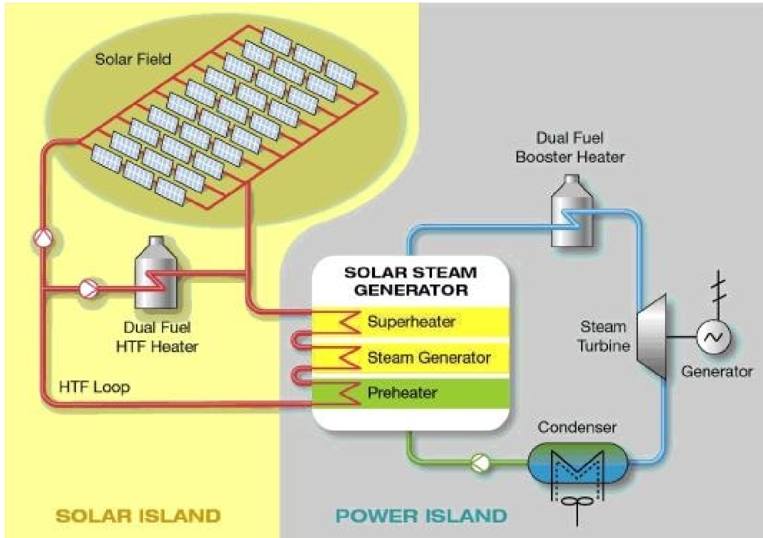


Figure 33. Shams-1 (Sun-1) Integrated Solar Combined Cycle (ISCC) solar power plant project, United Arab Emirates (UAE) is supplemented with a natural gas heater unit. HTF: Heat Transfer Fluid.

The plant is comprised of a solar field consisting of 768 parabolic trough collectors supplied by Abengoa Solar, plus a backup natural gas boiler to supply power when the sun is not shining. The plant will displace approximately 175,000 tonnes of CO_2 per year and directly contribute to the UAE's goal of 7 percent renewable energy by 2020.

The new Integrated Solar Combined Cycle (ISCC) plant will be jointly owned by Masdar (60 percent), Total (20 percent) and Abengoa Solar (20 percent). Construction commenced in the fall of 2010.

The project is located about 75 miles southwest of UAE capital Abu Dhabi and estimated to cost between $500 and $700 million and is expected to generate around 100 megawatts of power, and will be the world's largest Concentrating Solar Power plant (CSP) when completed by 2013.

Masdar currently operates a 10 MW Photo Voltaic (PV) power plant in Abu Dhabi. Unlike PV plants, which use solar panels that directly convert sunlight into electricity, ISCC reflect sunlight, usually with mirrors, heating liquids that produce steam to generate power and use natural gas to increase the capacity factor and overcome the intermittency problem.

FRACKING DIPLOMACY

Landowners are acquiring fortunes by allowing fracking on their land in the USA. Their neighbors complain about the possible contamination of their wells and surface water supplies. Unable to win the neighbor's love, the drilling companies engage in "fracking diplomacy." The oil and gas companies realize that their profitability depends as much on reputation management as on good engineering or strong geoscience skills. Community relations are also designated as "stakeholder management" in the jargon of the corporate world and is a critical aspect of operations for the mining and extractive industries.

Companies engage in “local philanthropy” to community initiatives and education to win the heart and minds of the surrounding communities in terms of environmental, social and corporate [11].

ALTERNATIVE SHALE NATURAL GAS STRATEGIES

Shale gas wells are subject to a fast decline after the first year of operation and must be propped multiple times. When the hydraulic fluid is pumped down to fracture the rock it also carries small particles of sand or a similar material. These grains are forced into the cracks to "prop them open" after the cracking pressure is released, and thus they are called proppants. But they can be quite hard, and if the rock is soft, or becomes soft after being wetted, then it can deform around them and close the fissures.

The micro fractures cannot be reached by the proppants. The proppant is used to hold open the much larger induced fractures. There is a peculiar characteristic to many of the shale gas wells that is not typically mentioned: much of the natural gas produced is not free gas. It is actually molecularly bound to the organic material in the shale. When the well is produced pressures in the rock decrease. This decreased pressure causes the molecules to become unstable and the methane molecules are released from the structure. Lower pressures release more methane but the lower pressures also cause the loading on the rock matrix to increase which, in turn, closes the fractures and reduces flow rates. The negative feedback loop eventually leads to a decreased production.

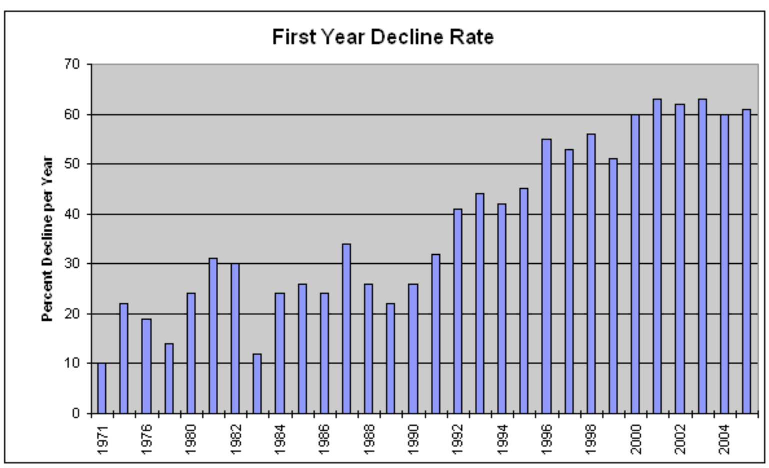


Figure 34. Barnett shale, Texas first year decline in gas production rate. Source: Swindell.

If one is lucky and hit and extensive natural crack system they have a profitable well. If the desorption is fast enough to keep the pressure up, the crack system is charged from the overburden above the shale.

One factor that drives some management teams to drill horizontally is the increased probability of making a commercial well even if the increased costs make the well less profitable than a series of vertical wells. Horizontal wells allow a better chance of intersecting fractures and statistically can connect up much larger areas through the micro cracks to larger crack network that gets intersected.

A series of vertical wells could be drilled and some would not be commercial and have to be plugged as a non-commercial well. Drilling all horizontal wells successfully but with a lower Rate Of Return (ROR) on the investment is usually justifiable. Recognition is given for a 20 million cf / day flow rate even when the ROR of the well is just 2 percent.

To avoid the high depletion rate of currently horizontally drilled shale gas wells, an alternative strategy has been suggested for their development. The cheapest vertical well is drilled and if it intersects a crack system then slow but steady earnings from these wells if there is any natural crack system will pay for further analysis and developing steady and profitable wells.

Developing a fracture system requires a driller to hit the fracture. The faulting in any open road cut that goes through a shale layer can readily be located where a road cut through a shale layer and the cracks caused but the geologic forces which are the key to these layers can be readily be observed and mapped before embarking on costly drilling.

Table 8. Breakeven prices for different shale gas sources, 2009. Data: Credit Suisse.

Formation, Source	Breakeven prices [$/mmBTU]
Haynesville, core area	3.63
Barnett, core area	3.49
Marcellus, horizontal	3.68
Hayneville, East Texas	5.04
Woodford	5.59
Marcellus, vertical	6.48
Average USA production	7.27
Powder River Basin	10.77
Qatar, USA market	< 5.0

REFINING AVAILABILITY

The 'light crude' that comes out of the 'fracking wells' has no refinery capacity in the USA that can refine it. It must be exported to places like South Korea. Therefore, the USA must import 'heavy and heavier crude' to refine here in the USA.

If the world became in a disrupted state, the USA would have as much problems getting that 'heavy crude' into the country, just like any other country needing oil. Everyone seems to forget about that fact or never knew about it.

EARTH TREMORS

The Cuadrilla Resources Company using hydraulic fracturing in drilling for natural gas from tight shale rock in the North-West UK near the Blackpool coastal resort reported that studies by independent experts concluded that some Earth tremors measuring 1.9 and 2.8 on the Richter magnitude scale in April and May of 2011 were due to an unusual combination of geology and operations and would be unlikely to reoccur again. Its operations were suspended on May 27, 2011 pending the studies. The resulting report suggests that a maximum magnitude could reach 3 on the Richter magnitude scale and would be barely felt at the surface [3].

Figure 35. Highway 62 buckling caused by 5.7 magnitude tremor, Prague, Oklahoma, 2011 [12].

At Prague, Oklahoma, a tremor cascade of magnitude 5.7 is suspected to be caused by wastewater injection, on November 6, 2011. The Prague earthquake was the largest of thousands of quakes that affected Oklahoma in late 2011. Three of them were of magnitude 5 or larger. The 2011 quakes struck along the Wilzetta fault zone near Prague. Earthquakes break faults like a boat plowing through thick ice. The fault zips open as the earthquake ruptures the fault, and then seals itself shut behind [12].

The magnitude 5.7 earthquake near Prague was preceded by a 5.0 quake that hit a day earlier, on November 5, 2011. This foreshock occurred near an active wastewater disposal well. Tremors linked with hydraulic fracturing are rarely triggered by the actual oil and gas extraction. They are caused by the waste fluid disposal in deep wells. The wastewater can lubricate and open fractures and faults, triggering tremors. It is suggested that the first tremor may have primed the fault for the larger tremor that hit the next day [12].

The boom in hydraulic fracturing in the central USA correlates with an uptick in seismicity, with moderate magnitude earthquakes increasing in the states of Colorado, Texas, Oklahoma, Ohio and Arkansas. The number of quakes in the central USA has increased 11 times in the past 30 years [12].

WASTE WATER SEISMICITY

Wastewater in hydrocarbons production is brackish water that naturally coexists with oil and gas within the Earth. As a part of the drilling and extraction process, the produced water is extracted from the oil and/or gas and is typically reinjected into deeper disposal wells. In Oklahoma, these wells are in the Arbuckle formation, a 7,000-foot-deep sedimentary formation under Oklahoma.

Industry has been disposing wastewater into the Arbuckle for 60 years without seismicity. Sime level of disposal is safe. One need to figure out the exact mechanism by which this wastewater injection is triggering the seismic events and modify our procedures to prevent them. In the area of the seismicity, ten barrels of produced water, which contains five times more salt than ocean water, is generated for each barrel of oil.

A Stanford study, by Professor Mark Zoback and doctoral student Rall Walsh, found that "the primary source of the quake-triggering wastewater is not so-called 'flowback water' generated after hydraulic fracturing operations." The fluid injection responsible for most of the recent quakes in Oklahoma is due to production and subsequent injection of massive amounts of wastewater, and is unrelated to hydraulic fracturing. Less than five percent of the waste water is hydraulic fracturing water. More than ninety percent of the new oil-and-gas wells drilled in the USA use hydraulic fracturing.

METHANE GAS LEAKAGE, HYDRAULIC FRACTURING ACHILLES HEAL

Methane leakage appears to be the Achilles' heel of hydraulic fracturing. It is well established that when natural gas is combusted, it has both environmental and climate change benefits, starting with the fact that natural gas emits half the carbon of coal. But that advantage disappears when too much methane leaks during any part of the production process.

According to the Environmental Defense Fund (EDF): "Methane is at least 28 times more powerful than CO_2 as a greenhouse gas over the longer term and at least 84 times more potent in the near term." Even though methane gradually loses its potency as a greenhouse gas over time, the environmental movement admits that natural gas may be cleaner, but it is still a fossil fuel. Thus it believes that an abundance of natural gas could delay the long-sought vision of a world powered by renewable non-carbon energy sources.

The EDF adopted approach is that, rather than calling, Don Quixote-style, for an end to hydraulic fracking, it is working with states like Colorado to make it safer, more transparent and cleaner. In 2011 the EDF helped negotiate rules governing the disclosure of the chemicals in fracking compounds. In Wyoming, it has negotiated rules to require groundwater testing near wells to detect any possible contamination. In Texas, it was involved in coming up with regulations for well integrity. In Colorado, it announced a set of proposed rules that would govern, and reduce, methane leakage. In each case, the EDF is pushing other states to adopt these rules, which, taken together, would help ensure that natural gas will live up to its promise of being a better, cleaner fuel.

The rules proposed in Colorado require producers to test for leakage on a regular basis, monthly in some cases. They will have to avoid methane venting from wells. They will have to retrofit the valves on wells to minimize leakage. The industry goes along with the tougher regulations because it needs to be able to show that it is going about it in a manner that is safe and environmentally sound.

USA NATURAL GAS NETWORK

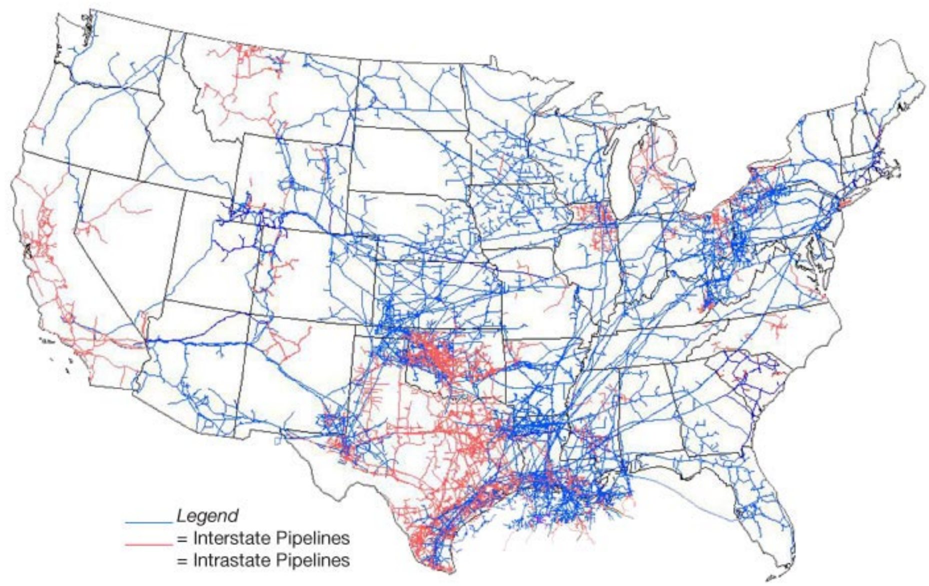


Figure 36. USA natural gas distribution pipeline network. Source: USA Energy Information Administration (EIA).

There exist about 210 systems of pipelines that carry natural gas to most parts of the USA, and about 1,400 compressor stations that maintain the driving pressure in the pipeline system. Gas is stored in underground tanks and in porous geological formations at more than 400 places.

There are more than 300,000 miles of gas pipelines underground in the USA in comparison to 470,000 miles of interstate highways and 250,000 rivers.

The state of Texas produces about 100 trillion cubic feet of natural gas per year, almost a third of the 335 trillion cubic feet produced in the whole USA. The state of Wyoming comes second, at about 35 trillion cubic feet. Louisiana, Oklahoma and Colorado follow. About 66 million homes burn natural gas as a heating and cooking source. Another 5 million commercial enterprises use natural gas which produces about half as much CO_2 per Btu as coal and about 75 percent as much as petroleum.

INNOVATIONS IN HYDRAULIC FRACTURING

ZIPPER FRACKING

In 2012, an innovation in fracking, called “zipper fracking” was introduced where the operators drill two wells side by side. Once they are completed, they are hydraulically fracked at the same time. The generated fractures form a zipper pattern that cracks the rocks more deeply and efficiently than in a single well. The process allows both wells to produce more oil and gas. In the Barnett Shale in Texas, the zipper-fracked wells doubled the volume of a typical well.

STACKED LATERALS

In the offshore oil industry several wells from a single pad. Onshore shale drillers are adopting the technique. Because shale is a uniform layer of rock, the wells can be drilled close to each other. Since the drillers do not have to move the rigs too far between holes, the method saves time and money. The process of taking down and setting up a drill rig can take days and is costly. Some hale layers, like those in the Bakken and the Eagle Ford and Permian Basin in Texas, are stacked like pancakes. Companies can drill many wells into these layers.

Table 9. Increased production per drilling rig from zipper and lateral stacking methods.

State	Shale region	Production. June 2011, [barrels /day]	Production. June 2014, [barrels /day]	Increase [percent]
Colorado	Niobrara	95	361	280
Pennsylvania	Marcellus	2,427 mcf/day	6,516 mcf/day	168
Texas	Eagle Ford	198	476	140
North Dakota	Bakken	213	505	137

DISCUSSION

With a dearth of available capital, and the natural gas abundance making it the cheapest energy option for gas turbine direct and combined-cycle power generation, the Exelon Corporation shelved plans to expand its capacity at two nuclear power plants. The Michigan utility CMS Energy Corporation cancelled a $2 billion coal power plant after deciding it was no more financially viable. Next Era Energy Incorporated, the largest USA wind energy producer, shelved plans for new USA wind projects. In 2010, the energy investor T. Boone Pickens shelved wind energy projects in northern Texas and focused on promoting liquid Compressed Natural Gas (CNG) fuel for the USA trucking fleet.

A report: “Fact-based Regulation for Environmental Protection in Shale Gas Development,” at the University of Texas found that “surface spills of fracturing fluids pose greater risks to groundwater sources than from hydraulic fracturing itself.” Spills at the drill site or problems with cement casing around upper well bores were examples of incidents that have led to shallow groundwater contamination in the USA. It argues that these problems are common in other forms of oil and gas development as well. It did not call for a strict new regulatory framework but suggested that individual states could take steps to supplement the regulations that are already in place.

On the other hand, the USA Environmental Protection Agency (EPA) is studying hydraulic fracturing to determine whether it affects the fresh water supplies, and initial results are not expected until 2014.

Figure 37. Protest against hydraulic fracturing at the White House, Washington D. C. Source: Bloomberg.

Figure 38. Protest against Hydraulic Fracturing, New York.

Figure 39. Protest against hydraulic fracturing, Germany. Source: Der Spiegel.

Figure 40. Fracking site next to an abandoned animal confinement facility.

Some jurisdictions are not waiting for the official study results. New York City and the city of Syracuse, New York, have banned hydraulic fracturing in their watersheds, citing a study that concluded that hydraulic fracturing could pose “catastrophic” risks to the prized local water supply. New Jersey is considering a ban. The city of Pittsburgh has prohibited the practice within city limits.

The Canadian province of Québec banned hydraulic fracturing completely, even though the province hosts a considerable shale gas potential. In Australia, hydraulic fracturing has been sweeping the Queensland countryside, and objection is building up among landowners. Shale exploration is similarly spreading quickly and causing concern across Europe.

In a hope for an economic boom to the State of Illinois, a bill passed the legislature by a wide margin regulating the fracking process. Firms are required to test the groundwater in the drilling region both before and after the fracturing process. SM Energy of Tulsa, Oklahoma drilled an exploratory well in Wayne County in southern Illinois on the Walt Townsend farm. The plan is to drill down to 5,000 ft and then at a horizontal slant for 3,000 ft. Land owners have sold mineral leases to energy companies that are likely to drill on their land. Others sold leases to what is referred to in the business as “lease jockeys” who lock up acres with the intention of “flipping” or selling them to the highest bidder. Some short leases are up for one year for renegotiation if drilling does not materialize. In some long leases, the land could sit there undrilled indefinitely. One company has spent 50 million dollars on acquiring leases [10].

Shale gas contributed about 0.5 percent to the USA GDP in 2013 and is a significant driver of jobs and growth. There are new shale gas prospects over the USA and Canada. The Continental Resources Company announced a major new shale gas field in Oklahoma in October 2011, with a comparable geology to that of the Bakken field.

The USA is expected to export Liquefied Natural Gas (LNG) by 2015-2016 from McAllen, Texas, and other LNG ports are in various stages of permitting. Natural gas is priced Japan at about $18 per million BTUs, compared to $3.78 in the USA. Europe is at $11.83.

The real advantage for the USA may not come in exporting LNG, but rather in the chemical byproducts from it such as fertilizers and feed-stocks for the chemical industries. Europe is complaining that cheap USA natural gas is encouraging a flight of its energy intensive businesses to the USA. Europe's chemical producers buying expensive Russian gas cannot compete with their USA competitors who are guaranteed access to cheap feed-stocks. The development of their native considerable shale oil and gas fields faces public resistance.

Natural gas is blazing a trail as a bridge fuel along the road of the implementation of renewable energy sources and an energy economy where hydrogen is used as an energy carrier with fuel cells replacing the Internal Combustion Engine (ICE). Natural gas could be used in the steam reforming process to produce synthetic gas which is a mixture of H_2 and CO. Instead of Carbon Separation and Storage (CCS), the process of carbon dioxide reforming would use natural gas to turn CO_2 into a useful product such as green diesel fuel that is free of engine-corroding sulfur. To overcome the intermittence property of thermal solar energy, the Integrated Solar Combined Cycle (ISCC) alternative uses natural gas in hybrid plants under construction to provide power during the night period and on cloudy days.

Technological hurdles need to be overcome. An issue is horizontal drill holes collapsing due to improper drilling techniques. The holes collapse can lead to expensive lost time on rigs, in addition to losing drill bits, pipe and equipment down holes and having to seal up a lost hole and redrill it over again. There is a need to understand the geo-mechanical properties of the drilling medium and the drilling mud quality and weight.

About one half of the fracking stages either do not function adequately from the start or fail soon after the well goes into production. Research and development is needed to address these issues and improve on the productivity of the drilled wells.

The shale oil and gas industry has not really made a profit since 2009, and is operating at a negative cash flow deficit if capital expenditures (CAPEX) and stock-holders' dividends are accounted for.

Fracking oil produces the highest output in the first year and then production drops of calamitously and they can only hide it by drilling new wells faster the old wells start to fail. They fail as in terms of not being able to pay the debts with low oil prices and the extremely high cost of fracking. USA oil production is going to drop and that may drive the next USA economic downturn. As the fracking companies collapse, so will the banks that finance them.

As the smaller players go bust, the major oils and banks buy them up on the cheap and claim they have added "reserves" which helps inflate their stock and increase their credit margins.

Table 10. Operational cash flow surplus (deficit) estimates of USA gas producers, $million. Data: Oppenheimer & Co., July 2015.

	Year 2015	Year 2016
Anadarco	(2,074)	(2,799}
Apache	45	270
Cabot Oil & Gas	(211)	(48)
Chesapeake	(2,021)	(2,747)
Conoco Phillips	(5,859)	(3,556)
Devon	(841)	(2,142)

EOG Resources	(1,631)	(1,133)
Hess	(2,288)	(1,295)
Marathon Oil	(1,493)	(1,171)
Murphy	(1,461)	(1,193)
Noble Energy	(1,040)	(743)
Occidental	(2,978)	(2,391)
Pioneer	(624)	(661)
Range Resources	(107)	(193)
Southwestern Energy	(200)	(171)
Total	(22,784)	(19,974)

Despite the remaining technological hurdles pertaining to environmental concerns, it must be admitted that the unconventional exploration for hydrocarbons, including hydraulic fracturing, is a phenomenon that will endure as a way to tap into the Earth's stored energy resources, even though it is coming under intense scrutiny. Natural gas is increasingly asserting its role as the bridge fuel of choice along the road of the implementation of renewable and carbon-free sources of energy.

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