ENVIRONMENTAL ISSUES RELATED TO ENHANCED PRODUCTION OF NATURAL GAS BY HYDRAULIC FRACTURING

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INTRODUCTION

Hydraulic fracturing occurs when high pressure fluids primarily consisting of water and sand are pumped at high pressure into subsurface formations, typically shale that contains natural gas and/or oil. The high pressure fluid causes the rock to fracture. The new fractures increase the surface area of the shale and better interconnect previously existing fractures, allowing more natural gas and/or oil to be pumped from the formation. Modern hydraulic fracturing, referred to as "fracking," is an evolving technology that largely began after 2000 and has significantly increased natural gas production in the United States in the past five years with corresponding decreases in natural gas prices.

The revolution in hydraulic fracturing has been made possible by technological advancements in directional drilling. In the past, wells were drilled vertically and sometimes passed only briefly into the producing formation. Shale is a sedimentary rock that is initially formed underwater as a horizontal layer containing compacted mud that is cemented into rock. Intact shale has a low permeability, making fluid movement slow except along natural or artificial fractures in the rock. In the case of the Marcellus Shale in Pennsylvania, the shale is approximately 100 to 250 feet thick. The Barnett Shale in Central Texas is between 100 and 500 ft, averaging about 300 ft; Eagle Ford Shale in South Texas is very variable with an average of about 250 ft; Fayetteville Shale in Arkansas is between 60–575 ft, average of about 200 ft; Haynesville Shale in Northwest Louisiana averages about 250 ft. Tectonic activity may later deform the initially horizontal layer into different angles and shapes, but the fundamental problem remains of how to most efficiently extract fluids from relatively thin and deep rock layers that have low permeability. Directional drilling allows a well to be oriented in a vertical direction until the shale layer is approached and then turned in to the approximately horizontal direction needed to follow along the shale layer (Figure 1). The wells can be turned in any compass direction, allowing multiple wells from a single pad to reach areas of several square miles in the producing shale location, thus significantly reducing their surface footprint and disturbance when

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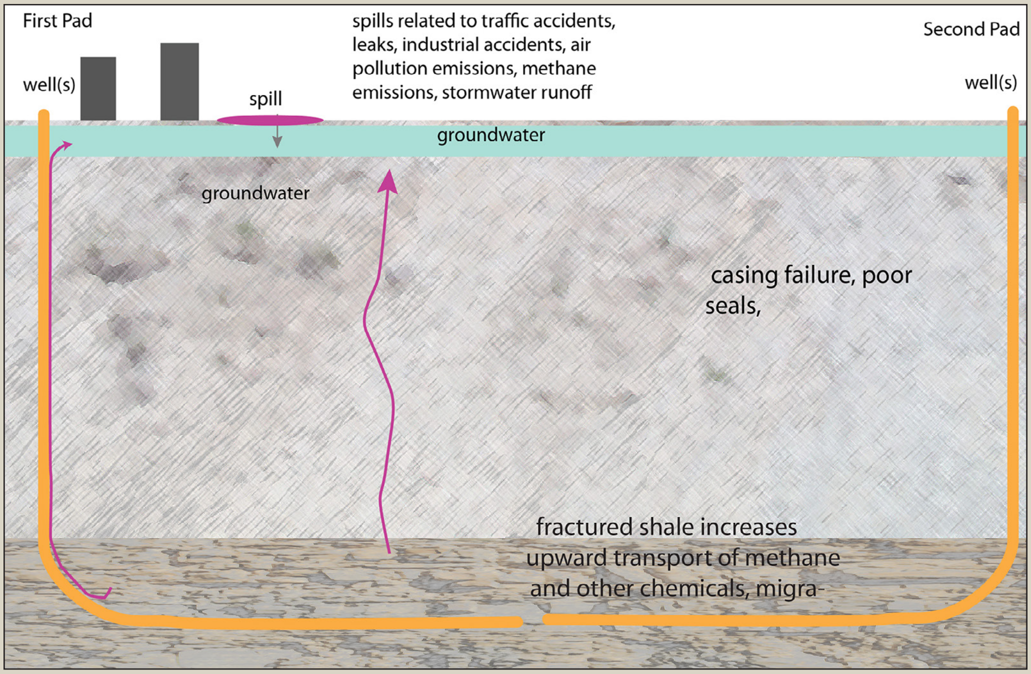
FIGURE 1. Schematic picture showing two pads and two wells.



compared to vertical drilling. Wells have been drilled more than a mile deep and a mile in horizontal reach. Furthermore, the Marcellus Shale is underlain by the thicker Utica Shale, making it likely that the same pads may years later be used to drill wells into the Utica Shale as well when gas prices rise sufficiently to make deeper drilling cost effective. Information on the extents of the Marcellus and Utica Shale formations is available in USGS reports listed in their Energy Resources Program (USGS, 2013) and at the website geology.com (Geology.com, 2013).

The second key to increased access to energy resources is hydraulic fracturing. Shales naturally have a low permeability, meaning removal of resources is slow and inefficient. High pressure fluids containing proppants (e.g., sand), biocides, friction reducers, corrosion inhibitors, iron control, scale inhibitors, surfactants, and acids are injected into the wells to cause fracturing of the shale. The proppants move into the newly created fractures and expanded natural fractures and then prop the fractures open when the fluids are removed. The injected fluid is primarily (~99.5%) sand and water and the additive mixtures change by location, company, and as the technology evolves. Much of the injected water is later extracted from the well during production, along with formation waters.

The exact spacing of pads, number of wells per pad, orientation of wells drilled from each pad, and well distance in the horizontal and vertical directions, depends upon surface access, drilling rights, formation properties, and economics. Leasing is an issue. Leases typically expire after a fixed period of time (typically about 5 years) if there *is no drilling activity. Companies can drill but choose not to hydraulically fracture or produce from the well prior to lease expiration in order to lock up the resources until the economics of production improve.*

Hydraulic fracturing has revolutionized the energy field, causing the United States to switch from a need to import natural gas to a situation where export of natural gas is being considered. Energy independence, low energy costs, and economic development are clear positives that have been advanced by the revolution in hydraulic fracturing.

This paper will summarize some of the environmental impacts associated with fracking. The order of subjects is approximately from the most obvious and certain to more subtle impacts.

KEYWORDS

environmental impact, fracking, land use and disturbance, water and groundwater contamination, hydraulic fracturing, risk, drilling

LAND USE AND DISTURBANCE

The Pennsylvania Energy Impacts Assessment (Johnson, 2010) estimated surface impacts in Pennsylvania as 7,000–16,000 new pads by 2030 with 60,000 new wells. Well pads were estimated as 3.1 acres and forest cleared for associated infrastructure (roads, pipelines, surface impoundments) was estimated as 5.7 acres per pad, totaling 8.8 acres per pad, or 138 square miles of new development in the State of Pennsylvania. The study estimated that nearly 2/3 of the new well pads will be in forested areas, including public lands.

This is a large environmental impact, particularly as the disturbance is distributed at regular intervals in currently undeveloped areas based upon the pad spacing. This contrasts with urban development that tends to be concentrated around urban areas rather than dispersed. Construction of the pad and associated infrastructure and access roads can impact the quality of local streams and lakes due to rain runoff containing sediments from the disturbed site. Typically drilling will take place in rural areas, requiring the construction of new roads whose associated environmental impacts can only be partly mitigated.

The impact of land disturbances can be reduced by mitigation strategies based on use of seeding and filter strips, in addition to terraces, check dams, filter fences, and straw bales. Proper selection of pad placements such as at the edge of forest patches (Johnson, 2010) can also reduce land use impacts.

Furthermore, as the technology advances, fracking play lateral reaches will increase thus allowing for fewer pads to cover the same play footprint and reducing their total impact.

NOISE

Drilling and hydraulic fracturing is a temporary, transient activity typically lasting a few weeks. Typical noise sources are the drilling rig (diesel generators, braking mechanisms and drilling pipe handling), large compressor, diesel electric generators, and truck traffic.

Noise nuisance can be mitigated through the installation of mufflers, baffles, and silencers on the pad's installation. Also, sound absorbing buildings can be constructed around compressor stations. A cost effective strategy that can minimize noise from initial operations is the use of tall plastic sound-barriers (acoustic walls), as these can be moved from site to site as needed. New more silent drilling rigs have been developed by some companies specifically to address noise issues.

TRAFFIC

The development will increase traffic on roads including truck traffic to the pads. Injected and produced water is mostly transported to and from the pads by truck. Increased traffic means more accidents and more localized air pollution. Site operations and the heavy traffic will increase noise levels. Transient workers can disrupt rural areas.

Pipeline networks facilitate transporting injected and produced water with reduction of truck traffic, but this increases construction and land disturbance. Flowback water storage, for its later reuse in other jobs, reduces the amount of water transported, but storage of water on the surface can lead to leaks with resulting surface and ground water contamination. Treatment of produced water can also reduce the amount of water transport. Reduction of truck traffic is also in the best economic interests of the operator and is weighed against the cost of infrastructure construction for transport, reuse, and treatment of fluids. If local sources of water are available to a pad then truck traffic of injection water can be reduced.

WATER, FLOWBACK WATER, AND SURFACE SPILLS

Hydraulic fracturing requires the injection of water and additives at high pressure to fracture the rock and then prop open the fractures sufficiently to allow the trapped gas to escape. (Kaufman, Penny, & Paktinat, 2008). The injected water leads to concerns of water use, especially in semi-arid climates, groundwater contamination, and surface water/shallow groundwater contamination from the water returning up the well. The natural rock is heterogeneous and has existing fractures and this means that the path and extent of the induced fractures is difficult to predict and/or control. A concern is that the newly fractured wells will intersect with abandoned wells increasing the risk of gas migration and well blowout or decreasing the effectiveness of fracking operation. The volume of fluid injected is highly variable but on the order of a million gallons per well. Hydraulic fracturing may be performed in a series of 6–9 frac stages per well. Subsequent to fracturing some fluid returns up the well immediately (flowback water) and some is produced with the gas (produced water). This is a mixture of the injected fluid and the formation water and the distinction between flowback and produced water is somewhat arbitrary.

The additives include (Kaufman, Penny, & Paktinat, 2008):

- *Proppant*—Small solids are used to prop open the fractures. The particles should have a specific gravity only slightly above that of water in order to be transported effectively and have high compressive strength. Sand, treated sand, ceramics, and resin coated walnut shells are examples.
- *Friction reducer*—Friction reducers are required to reduce pressure loss while pumping at high rates (50 to 120 barrels per minute) down the long, narrow (~6 inch) pipes. Common friction reducers are anionic, cationic, and nonionic polyacrylamide-based

and applied at the rate of ~0.025% of the fluid. These work by reducing the relative roughness at the pipe/water interface.

- *Biocides*—Injection of water containing sulfate (an oxidized compound) will promote growth of sulfate-reducing bacteria that produce hydrogen sulfide and black iron sulfide deposits on the pipes. Common biocides are quaternary amines, glutaraldehyde, tetra-kis-hydroxylmethylphosphonium sulfate, and tetrahydro-3,5-dimethyl-1,3,5-thiadiazinane-2-thione. Reuse of flowback and produced water is another application for biocides as the bacteria can attack the friction reducing polymer.
- *Scale inhibitors*—Scale can form on pipes and above ground equipment, lowering flow rates and production and sometimes precipitating naturally-occurring radioactive material (NORM). Most available scale inhibitors are phosponates and organophosphonates.
- *Clay stabilization*—Shales are formed from muds that had a high percentage of clay minerals. Some of the clays will come back with produced water. KCl is sometimes used for clay stabilization.
- *Surfactants*—Surfactants promote draining of small fractures because they lower the surface tension that holds water in small pores and fractures. Formulation of surfactants in an emulsion promotes the surfactant going to the leading edge of the fluid where it can be more effective.
- *Acids*—Acids such as HCl dissolve cementing minerals (e.g., calcium carbonate), helping to initiate fractures.

Increasingly, due to water supply and environmental concerns, fracturing water coming from flowback and produced waters is stored and reused in other or the same wells.

The primary threat to surface water and shallow groundwater from hydraulic fracturing is from spilled or released material on the earth's surface. Water coming back up the well can be stored in surface impoundments or tanks, either of which can leak. Water may also be treated then released to surface water, pumped offsite, or trucked offsite. Spills can occur during the pumping and/or hauling. Chemicals used in hydraulic fracturing must be transported to and stored at the site, providing more opportunity for spills and accidents. Construction of new roads and pads increases the potential for erosion and sediment generation from stormwater runoff. Pipes, valves, joints, and tanks can leak. Human errors can and will occur. Accidents will result in localized contamination of surface and shallow groundwater with any of the chemicals associated with drilling, hydraulic fracturing, and gas production.

Proper road building with adequate culverts and steps toward erosion control can minimize sediment generation. Fracturing fluids, flowback, and produced water can be stored in tanks with secondary containment. Chemicals can be safely stored and transported.

SUBSURFACE ISSUES

A key issue related to hydraulic fracturing is the potential migration of methane and other chemicals from the wells and shale formations into groundwater aquifers. Wells are normally completed far below the depth of groundwater aquifers by about a factor of 10 (thousands of feet for gas versus hundreds of feet for useful water). For this reason the greatest threat to groundwater quality is from spills on the surface that infiltrate downward into the groundwater. Water quantity is also a concern given the millions of gallons of water used in the fracking process.

Methane is a common naturally-occurring compound that is frequently present in groundwater at low concentrations and sometimes at high concentrations. For example, the USGS (White & Mathes, 2006) found that methane concentrations in West Virginia in 170 wells spread throughout the state ranged from 0 to 68.5 mg/L. Methane was detected in 131 of the 170 wells sampled and concentrations greater than 28 mg/L—where fire safety becomes a concern—were found at 13 wells. The presence or absence of methane (e.g., videos of homeowners lighting their water spigots) does not necessarily indicate anthropogenic contamination of their groundwater. Methane is a mobile compound in the environment and migrated prior to the addition of pathways related to drilling.

Methane (and potentially formation fluids and fracking additives) might reach groundwater along the preferential pathways caused by drilling. An ongoing EPA study (US Environmental Protection Agency, 2012) identified four scenarios for subsurface migration from below upward from the shale to a groundwater aquifer.

- Scenario A: Defective or inadequate well construction creates a migration pathway through the cement seals along the well bore and/or in damaged rock near the well bore, from the gas reservoir upward to the groundwater aquifer.
- Scenario B: The rocks just above the shale are fractured, allowing upward migration to the aquifer.
- Scenario C: Sealed or dormant previously existing cracks or faults are activated by the hydraulic fracturing, creating an upward migration pathway.
- Scenario D: Hydraulic fracturing creates a migration pathway to other existing wells (perhaps old, poorly-documented wells) that have defective seals along the wellbore.

Osborn (Osborn, Vengosh, Warner, & Jackson, 2011) found isotopic evidence of methane migration into overlying groundwater in Pennsylvania and New York. They analyzed 68 wells in northeast Pennsylvania and upstate New York for dissolved constituents and stable isotopes. The shallow groundwater in active drilling areas had higher methane concentrations and isotopic signatures consistent with thermogenic (deep) methane. Non-active areas had lower methane concentrations and isotopic signatures more consistent with biogenic or mixed methane sources. The study had a limited number of wells and did not have the type of before-and-after drilling data that could clearly establish that the elevated methane levels were caused by hydraulic fracturing related drilling. With respect to abandoned wells, some authors, such as Subra (Subra, 2010), suggest that regulatory mechanisms be implemented to identify, evaluate, and track orphaned wells, in order to avoid intersecting these while conducting hydraulically fracturing.

NATURALLY OCCURRING RADIOACTIVE MATERIALS (NORM)

The shale formations that contain natural gas also contain naturally-occurring radioactive elements including uranium, thorium, radium, ^{210}lead, and their decay products. These materials come up with the produced waters and can be concentrated when minerals present in the produced water precipitate from solution to form pipe scales and sludge. Scale that forms in pipes and gas dehydrators is composed primarily of low solubility calcium, barium, and strontium compounds that precipitate from the produced waters. Radioactive radium tends to go into solid solution with the other precipitating ions and thus becomes concentrated in the scale. Radon gas decay products polonium-210 and lead-210 may accumulate in the inside surfaces of plant equipment. If produced waters are treated offsite (e.g., local treatment plant, tanks used for hauling) then similar concentrative effects could become problematic. Operation and disposal of equipment can be a concern, particularly if nuclear safety is not considered in equipment salvaging operations.

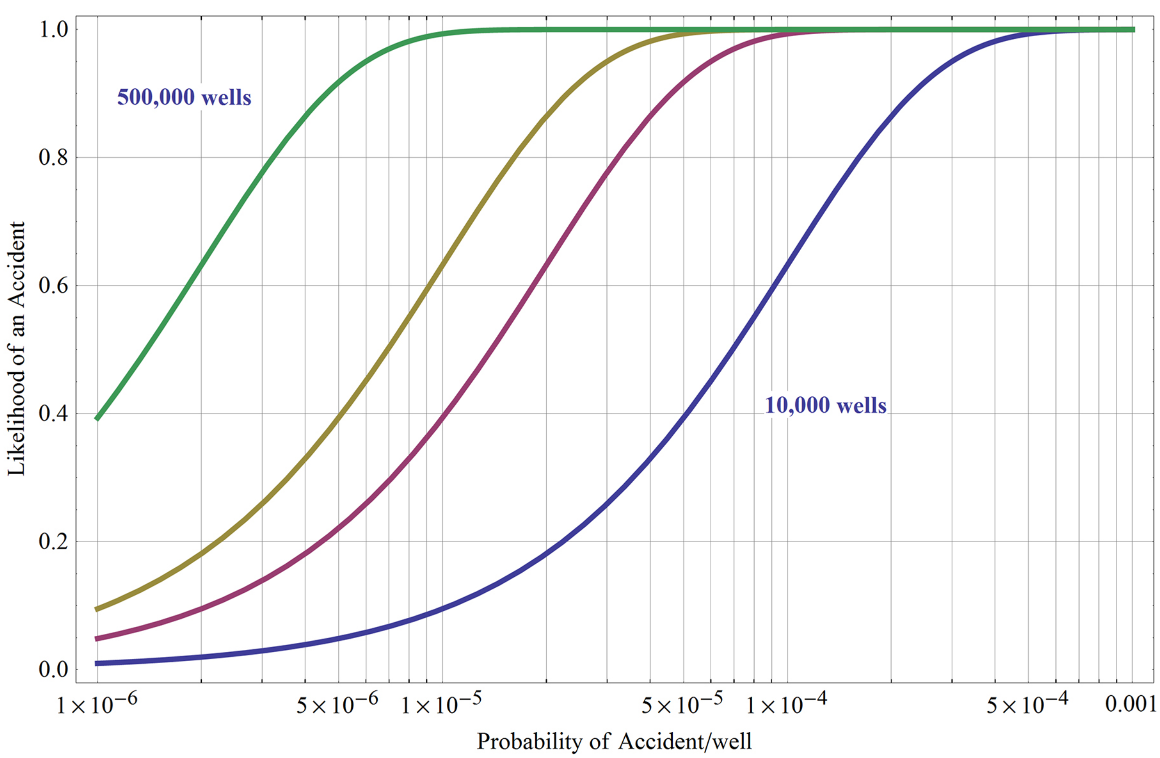
Prevention of barium, strontium, and calcium precipitation is a consideration for reuse of waters. Ideally the divalent cations will be kept in solution so that they, and the radium that tends to co-precipitate with them, are reinjected.

ACCIDENTS

As much as anything, hydraulic fracturing technology means a large increase in industrial activity—more wells, pads, trucks, etc.—in many areas that are now rural. The technology is new and rapidly evolving. Many of the potential impacts result from upset conditions and accidents. The casing or seals fail in the well, leading to groundwater contamination. A pipe, tank, connector, or valve fails leading to a surface spill of contaminated water. Operator error might lead to an explosion. Increased truck traffic means more traffic accidents. Most truck accidents occur at ramps and intersections and lead differentially to deaths and injury of small vehicle drivers rather than the truck drivers. The truck accident rate in the rural areas associated with fracking will be higher than numbers based primarily on interstate highway driving.

The frequency and consequences of these accidents will depend upon the safety standards applied by industry and regulatory agencies, but they will periodically occur given the high number of wells anticipated and the complex and varied nature of the subsurface

FIGURE 2. Probability of one or more accidents.



environment. A simple calculation puts this in perspective. Each of the accident types has a frequency or likelihood.

Using the binomial distribution we calculate the probability of one or more accidents occurring as a function of the number of wells drilled and the frequency of each type of accident. At the extreme left side of the graph in Figure 2 are rare, potentially serious events (e.g., a blowout or explosion) that are assumed to be one in a million events. Moving to the right are more common accidents such as minor spills or traffic accidents that are assumed to occur at one out of 1,000 wells drilled. The different lines represent the number of wells drilled and operated with lines for 10,000, 50,000, 100,000 and 500,000 wells. As the number of wells increases, accidents that were infrequent become likely. The US EPA estimates that, as of 2012, 11,000 hydraulically fractured gas wells are being added each year (US Environmental Protection Agency, 2013). Hydraulic fracturing, to be effective, requires a large number of wells. Accident frequency can be lowered by adopting a culture of safety.

ATMOSPHERIC EMISSIONS

Emissions of dust and diesel fumes are generated from truck traffic and construction of roads and drill pads. Emissions from drilling and fracturing are mostly due to engine exhausts and fugitive vapor from fracturing fluids, and include nitrous oxides, diesel fumes, volatile organic compounds (VOC), hazardous air pollutants (HAP, such as methanol), and fine particulates (PM2.5). VOC emissions due to extraction depend on the composition of the gas in the reservoir and are typically rich in BTEX compounds (benzene, toluene, ethylbenzene and xylene). Shale gas typically has negligible concentrations of H_2S. Emissions from compressor engines are nitrous oxide, carbon monoxide (CO), PM2.5, as well as VOC, and HAP emissions.

Low emission completion equipment (sometimes called green completions) has been developed to lower methane emissions from pads and to improve recovery. The idea behind green completions is to separate and capture natural gas from the flowback water during the clean-up stage of a completion. The EPA natural gas star program (http://www.epa.gov/gasstar/) represents industry/government collaboration on cost-effective strategies to reduce methane emissions. The recommended technologies and practices are organized in categories of compressors/engines, dehydrators, inspection and maintenance, pipelines, pneumatics/controls, tanks, valves, wells, and "other".

Fugitive releases of methane, ethane, propane, and other volatile organic compounds from leaks and pressure-relief venting valves, flowback water, and other production activities can potentially increase regional problems with ozone. Local factors influencing ozone buildup are snow cover and temperature inversion in the atmosphere above a site. On April 17, 2012, the EPA issued new regulations intended to limit air pollution emissions from the oil and gas industry (US Environmental Protection Agency, 2013). The regulations require equipment to separate gas and liquid hydrocarbons from the flowback waters in order to increase energy efficiency and reduce volatile organic compound emissions from the well sites. The equipment will also lower emissions of air toxics such as benzene, ethyl benzene and n-hexane.

GLOBAL WARMING

Global warming impacts are a controversial and unresolved aspect of the shale gas revolution. Carbon dioxide and methane are both powerful greenhouse gasses. Burning of methane produces lower carbon dioxide emissions per unit of energy production than coal or oil.

However, since methane is a greenhouse gas itself, fugitive emissions of methane (e.g, from the wellhead, pipelines, processing centers, homes) could potentially cause natural gas to have a greater greenhouse impact than coal. The IPCC (United States Environmental Protection Agency, 2013) (Intergovernmental Panel on Climate Change, 2007) estimates a Global Warming Potential for greenhouse gases based upon the total energy a gas absorbs over a 100-year period relative to carbon dioxide. On a mass basis methane has a Global Warming Potential 21 times greater than carbon dioxide, although the half-life of methane in the atmosphere is a relatively short 12 years versus hundreds of years for carbon dioxide. Depending upon the fraction of produced methane that escapes as fugitive emissions to the atmosphere, and the timeframe considered (tens of years or hundreds of years), a switch from coal to natural gas could either increase or decrease the rate of human-caused global warming.

One study (Howarth, Santoro, & Infraffea, 2011) estimated that 1.9% of the methane produced from fracking is released as fugitive emissions at the wellhead. Total fugitive emissions were 3.6 to 7.9% of production. Over a 20-year time period the greenhouse effects of fracked gas exceeded that of coal and over a 100-year time frame were comparable to coal.

In contrast, another study (Jiang, Griffin, Hendrickson, Jaramillo, VanBriesen, & Venkatesh, 2011) compared Marcellus shale gas with electricity from coal and estimated the greenhouse impacts from natural gas were lower than coal. A major part of the difference was the estimate of fugitive emissions of methane. Lifecycle impacts of different technologies are difficult to assess, particularly when hard-to-quantify aspects such as fugitive emissions are of critical importance. Green completion of wells, where gas and liquid hydrocarbons are separated from flowback, will reduce well-site methane emissions and is now required by the EPA. This shifts the balance back towards gas being preferable to coal.

An alternative perspective is that comparison with coal is inappropriate. By lowering the cost of fossil fuels, hydraulic fracturing technology lowers the economic viability of renewable energy sources such as solar and wind energy, thus delaying the transition to a renewable energy economy. By expanding the economic viability and timeline of the carbon-based energy economy, hydraulic fracturing technology increases greenhouse gas emissions and thus global warming.

CONCLUSION

Key impacts are:

Positive

- Lower-cost natural gas with associated lower electricity rates will improve the standard of living for nearly everyone in the US
- The economic activity associated with new oil and gas drilling will create thousands of new mostly high-paying jobs; many of these jobs do not require a college degree, meaning that they may also help with income inequality
- Lower energy prices make U.S. industry more competitive worldwide

Negative

- Significant land areas, many currently in natural states, will be developed
- The impacts to natural areas will be dispersed on a grid spacing rather than concentrated as is the case for most land development

- Noise, traffic, and human resource issues will impact rural areas
- Accidents leading to air pollution, water pollution, and loss of life will occur
- Lower energy costs will extend the fossil fuel–based economy, thereby delaying the transition to renewable energy sources, with consequent increases in greenhouse gas emissions

The most significant environmental impacts from hydraulic fracturing are a result of the large degree of industrial activity required, the high number of wells associated with removing resources from a tight formation, and the distributed nature of the resource. A large number of well pads must be developed and distributed over a broad area rather than concentrated. Dispersed, transient, heavy industrial activities have a variety of fairly well understood environmental ramifications as described in the sections above. Contamination of groundwater resources by the subsurface operations, while it will sometimes occur, will not be the major environmental impact of unconventional gas extraction.

The environmental problems related to hydraulic fracturing can be minimized, but not eliminated, by careful regulation that adheres to current best practices, encourages the improvement of technology and the further development of better practices.

REFERENCES

Geology.com. (2013). *Utica Shale—The Natural Gas Giant Below the Marcellus*. Retrieved from http://geology.com/articles/utica-shale/

Howarth, R., Santoro, R., & Infraffea, A. (2011). Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change, 106*(4), 679-690.

Intergovernmental Panel on Climate Change. (2007). *Climate Change 2007: Working Group I: The Physical Science Basis*. Retrieved 1 4, 2013, from IPCC Fourth Assessment Report: Climate Change 2007: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ts.html

Jiang, M., Griffin, W., Hendrickson, C., Jaramillo, P., VanBriesen, J., & Venkatesh, A. (2011). Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett., 6*, 9.

Johnson, N. (2010). *Pennsylvania Energy Impacts Assessment.* Nature Conservancy.

Kaufman, P., Penny, G. S., & Paktinat, J. (2008). *SPE 119900 Critical Evaluations of Additives Used in Shale Slickwater Fracs.* Society of Petroleum Engineers.

Osborn, S., Vengosh, A., Warner, N., & Jackson, R. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings National Academy of Sciences, 108*(20), 8172-8176.

Subra, W. (2010). *Methane and Volatile Organic Chemicals in Air in DISH.* Washingnon, DC: Earthworks.

United States Environmental Protection Agency. (2013). Retrieved 1 4, 2013, from Greenhouse Gas Emissions: http://epa.gov/climatechange/ghgemissions/gases/ch4.html

US Environmental Protection Agency. (2012). *Study of the potential impacts of hydraulic fracturing on drinking water resources—progress report.* USEPA.

US Environmental Protection Agency. (2013, 1 4). *Oil and Natural Gas Air Pollution Standards*. Retrieved from http://www.epa.gov/airquality/oilandgas/index.html

USGS. (2013, January). *Energy Resources Program*. Retrieved from http://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment/USBasinSummaries.aspx?provcode=5067

White, J., & Mathes, M. (2006). *Dissolved-gas concentrations in groundwater in West Virginia, 1997–2005.* USGS.